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PREFACE

This issue of the Quarterly TRANSACTIONS, which is Part 1 of Volume 50, is dated March 1931 in accordance with a recently adopted change in publication dates. Hereafter the four parts of the TRANSACTIONS will be issued in March, June, September, and December, instead of January, April, July, and October as formerly. This change was made necessary because the publication work in connection with the Winter Convention has increased to an extent which seriously interferes with the publication of the TRANSACTIONS in January.

This volume contains the papers and discussions presented at the Pacific Coast Convention at Portland, Oregon, September 2-5, 1930, the Middle Eastern District Meeting at Philadelphia, Pa., October 13-15, 1930, and at the Southern District Meeting at Louisville, Kentucky, November 19-22, 1930.

A table of contents appears in the front of the book and an authors' index of papers in the back. The complete alphabetical subject and authors' index for the year will be printed in the December Quarterly.

Critique of Ground Wire Theory

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Synopsis.—The paper consists of three parts, I—Induced Potentials, II—Direct Hits, and III—Other Effects. The work of previous investigators is briefly reviewed, and the limitations of their premises pointed out. Under Part I a generalized theory of ideal ground wires is offered, which takes into account the law of cloud discharge, the distribution of bound charge, and the formation of traveling waves. It is found that the protective ratio is independent of these factors. A more extensive theory taking the additional factors of successive reflections and tower resistance into account is then developed. Part II discusses the probability of a line's being hit, and applies a method for computing the effect of successive reflections to the calculation of potentials on the line and ground wires. Curves of these potentials at successive towers, and as functions of tower resistances and of time, are given. Part III discusses the effect of ground wires on attenuation, telephone interference, zero phase sequence reactance, corona, and the reduction in surge impedance due to the introduction of extra ground wires. There are three mathematical appendixes. In Appendix I, Maxwell's electrostatic and electromagnetic coefficients are reviewed, and the theory of traveling waves on any number of parallel wires is developed, including the behavior of these waves at rather general transition points. While this extension to the theory of ground traveling waves was developed incidental to the study of ground wire theory, it is believed to be of considerable interest and value on its own account. Appendixes II and III are the mathematical analyses corresponding to Parts I and II respectively.

INTRODUCTION

THE purpose of this paper is to extend and generalize the theory of ground wires, with respect to both induced and direct strokes, and to give a résumé of all the pertinent data which, in the opinion and experience of the author, represent the present status of knowledge on the subject. It is recognized, of course, that the facts available to the author cannot even approximately include all of the worth while information on ground wires, nor is his judgment infallible. However, in light of the present intense interest in ground wires, it seems advisable to present the ideas contained herein. This study is part of a coordinated investigation of lightning which has been under way for a number of years under the general direction of F. W. Peek, Jr.

The paper is divided into three major parts: I, Induced Potentials, II, Direct Hits, and III, Other Effects. The mathematical analysis is confined to the Appendixes, and only such equations are included in the text as are necessary to insure continuity of treatment and clarity of understanding. Incidentally, there is given in Appendix I a treatment of the characteristics and behavior of traveling waves on any number of mutually coupled parallel wires terminating in general impedances, including other outgoing lines.

I. INDUCED POTENTIALS

Review of Previous Investigations. When a charged cloud approaches a transmission line, charges of opposite sign leak over the insulators, or migrate from the line terminals, and appear on the line and ground wires as bound charges fixed in position by the electrostatic field of the cloud, Fig. 1a. The distribution $f(x)$ of any bound charge is proportional to the electric field G, but the actual magnitudes of charge on the several conductors depend upon their size, heights, and arrangements. These geometric factors are uniquely accounted for by Maxwell's coefficients, as described in Appendix I. Now when the field collapses according to some law $F(t)$ of cloud discharge, the bound charges on the line and ground wires are released and form pairs of traveling waves moving in opposite directions away

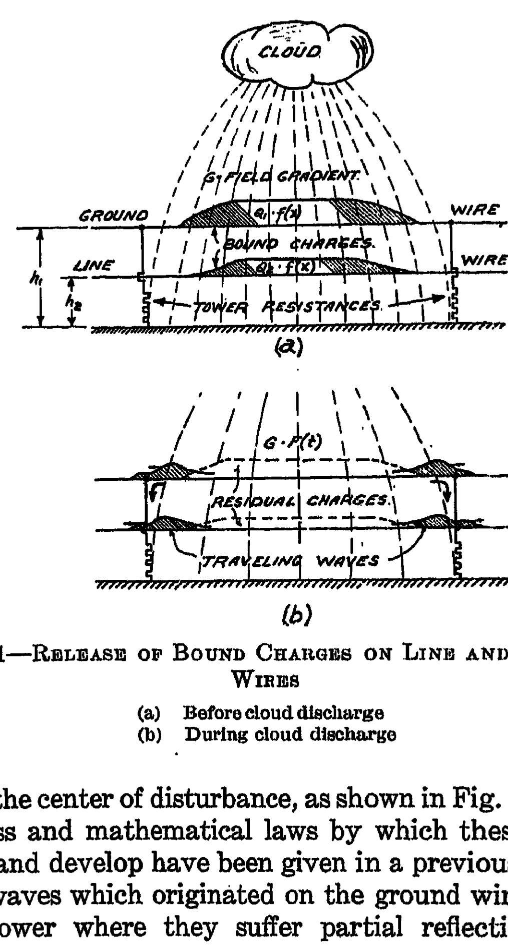

FIG. 1—RELEASE OF BOUND CHARGES ON LINE AND GROUND WIRES

(a) Before cloud discharge
(b) During cloud discharge

from the center of disturbance, as shown in Fig. 1b. The process and mathematical laws by which these waves form and develop have been given in a previous paper.[1] The waves which originated on the ground wires reach the tower where they suffer partial reflections and refractions, the extent of which depends upon the relative values of the surge impedances of the circuits and the tower resistance. However, unless the cloud

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1. For references see bibliography.

discharge is instantaneous, diminishing residual bound charges remain on the line and ground wires up until the cloud discharge is completed.

The conventional method for calculating the protective ratio (defined as the ratio of the voltage on a line wire with ground wire protection, to the voltage which would exist without ground wire protection) is based on the tacit assumptions that (a) the ground wires are "ideal," that is, perfectly grounded throughout their length, (b) the cloud discharge is instantaneous, (c) traveling waves are not formed, (d) the distribution of bound charge is uniform.

The published theoretical work which has been done with ground wires grounded through resistances[2,3], has also been confined to the case of rectangular bound charges instantaneously released, and subject to the further restrictions of a single ground wire, and a single line wire, although the possibility of introducing an equivalent ground wire and an equivalent line wire was erroneously supposed. Moreover, reflections were limited to a single span. These several simplifying assumptions were introduced in the interests of engineering practicability, and primarily for the purpose of obtaining qualitative results. In the opinion of the present author, the above work was a commendable step forward. The equations which were used, though derived in a different manner, are the same as those given in Appendix III, Equations (3), (4), (5), (6) of this paper.

Peek[4] has made extensive tests on models to ascertain the protective ratio for numerous different arrangements of ground and line wires. Some of his results are given in Table I of this paper. Of course, with tests made in a laboratory there is no room on the model transmission line for the development of traveling waves, and the conditions are inherently static. However, as will be shown, for ideal ground wires the protective ratio is independent of the formation of traveling waves.

Peek's tests show consistently lower protective ratios than those computed by the conventional method. Hunter[5] has attempted to account for this discrepancy as due to the formation of corona, resulting in an enlargement in the effective size of the conductor, and a corresponding reduction of induced potential. His method consists in solving for the charge Q_1 on the ground wire from the equations which obtain before cloud discharge (Equations (1), Appendix II of this paper). Then

$$Q_1 = G \cdot f(r)$$

where G is the field gradient due to the cloud and $f(r)$ is a function of the radii of the conductors. The gradient at the surface of the ground wire due to Q_1 is

$$g = \frac{2\,Q_1}{r_1} = 2\,G\,\frac{f(r)}{r_1}$$

Equating this expression to Peek's equation for the visual corona gradient[4]

$$g_v = 29.8 \left\{ \frac{1 + 0.301}{\sqrt{r_1}} \right\}$$

yields an equation

$$G = 14.9 \left\{ 1 + \frac{.301}{\sqrt{r_1}} \right\} \frac{r_1}{f(r)}$$

from which r_1 may be determined. This value of r_1 is then used in computing the protective ratio by the conventional method. Thus r_1, and with it the protective ratio, depends upon the field gradient G. A number of implied assumptions underlies this work, such as the supposition that corona obeys the same law under transient conditions as under steady state conditions, that it remains constant during the cloud discharge, that positive and negative corona are alike, and that there is no time lag. These limitations were recognized by Hunter. Nevertheless, his calculations agree very well with Peek's tests, and represent the only real effort to take the effects of corona into account. Some of his results are given in Table I, and a set of curves extracted from his paper is reproduced here as Fig. 2.

TABLE I
COMPARISON OF CALCULATIONS AND TESTS

Arrangement		Peek's tests on models	Hunter's method
. 0 0 0 1 2 3	(1) (2) (3)	0.52 0.44 0.52	0.57 0.47 0.57
. . 0 0 0 1 2 3	(1) (2) (3)	0.40 0.34 0.40	0.38 0.25 0.38
. . . 0 0 0 1 2 3	(1) (2) (3)	0.34 0.28 0.34	0.31 0.24 0.31
. 0 0 1 0 0 · 2 0 0 3	(1) (2) (3)	0.42 0.49 0.56	0.46 0.52 0.56
. . 0 0 1 0 0 2 0 0 3	(1) (2) (3)	0.33 0.38 0.44	0.27 0.33 0.40

McEachron, Hemstreet, and Rudge[6] have studied the ground wire effect with traveling waves, Fig. 4a, and have ingeniously separated the total effect into two parts, first, the reduction in voltage due to the escape to ground of the bound charge on the ground wire; and second, the further reduction in voltage due to the acquisition of a charge of opposite sign by the ground wires. Their results are in excellent agreement with calculations of the protective ratio by the conventional method. Corona did not enter into the picture, as the potentials of the impressed waves were relatively low. They found that tower footing resistance of the order of 75 ohms was practically equivalent to perfect grounding, as far as induced strokes are concerned. The effect of this resistance is easily calculated by Equations (3),

(4), (5), and (6), Appendix III, of this paper. By these equations the voltage wave on the line wire transmitted beyond the grounding point is

$$f_2'' = f_2 - \frac{Z_{12}}{2\,R + Z_{11}}\, f_1$$

Using calculated values of $Z_{11} = 532$, $Z_{12} = 107$, $R = 76$, and $f_1 = f_2$ (since the same wave was applied to all three conductors) there is

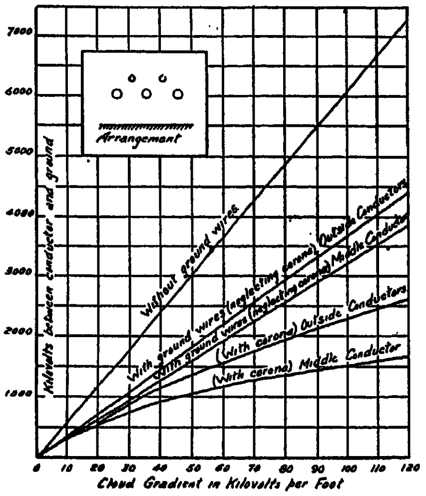

FIG. 2—HUNTER'S CORRECTION FOR CORONA

$$f_2'' = \frac{2 \times 76 + 532 - 107}{2 \times 76 + 532}\, f_1 = 0.845\, f_1$$

The value actually measured was 0.835. Had the grounding resistance been equal to zero this would have reduced to

$$f_2'' = \frac{532 - 107}{532}\, f_1 = \quad 0.800\, f_1$$

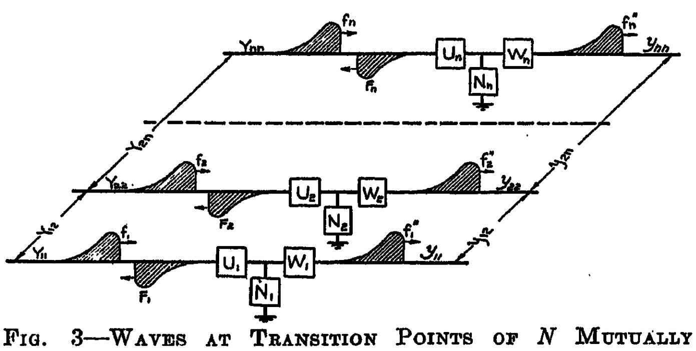

FIG. 3—WAVES AT TRANSITION POINTS OF N MUTUALLY COUPLED CIRCUITS

as compared with a calculated protective ratio (based on the conventional method) of 0.77. The difference is due to the fact that the conventional method for calculating the protective ratio takes into account the difference in voltage between wires at unequal heights, whereas the above calculations with traveling waves were based on the same initial waves on both conductors.

A number of measurements with antennas has been taken in an effort to obtain field data on the protective ratio afforded by ground wires. Smeloff and Price[7] mention one record in which a protective ratio of approximately 50 per cent was indicated. Here again, there is no room for the formation of traveling waves, and the situation is inherently static. The indicated protective ratio is of the order of that calculated by the conventional method,—certainly within the range of accuracy of the measurements.

The author hardly feels justified in mentioning in connection with induced strokes, the statistical data on ground wires that have been accumulated by operating companies, for there is no definite information as to the percentage of outages caused by induced and direct strokes. However, the interesting curves given as Fig. 9 in the paper by Lewis and Foust[8] show some degree of correlation between theory and experience.

From the foregoing review of the work that has been done on induced strokes, it is evident that no single study has explicitly included all of the essential factors

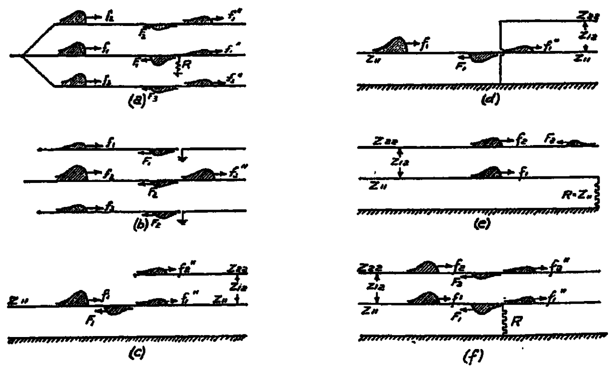

FIG. 4—WAVES ON MUTUALLY COUPLED WIRES

involved, nor has any definite effort been made to correlate the different methods of attack on the problem, so as to prove their equivalence. It is not entirely obvious, for example, that the same protective ratio would be found in the case of tests with traveling waves (a strictly dynamic situation) as are calculated by the conventional method based on purely static equilibrium conditions. It is still less obvious that either of these methods gives the same protective ratio as obtained under actual conditions. Table II outlines the assumptions underlying the several methods of attack, and serves to indicate their limitations from the standpoint of rigorous analysis. It is partly the purpose of this paper to correlate these separate investigations by contributing a generalized theory of ideal ground wires, and an extension to the theory of periodic resistance grounds.

Ideal Ground Wires. In Appendix II of this paper, the general theory of ideal ground wires (ground wires perfectly grounded at all points) is worked out. The analysis includes the effects of the law of cloud dis-

TABLE II
INVESTIGATIONS OF GROUND WIRE PROTECTION FOR INDUCED VOLTAGES

	Method	Considered the effect of:											
		Distribution of bound charge	Law of cloud discharge	Residual charges	Formation of traveling waves	Developed traveling waves	Corona	Tower resistance	No of spans	Successive reflections	No. of ground wires	No. of line Wires	Remarks
THEORETICAL	Conventional (Petersen)	No	No	Yes	No	No	No	No	No	No	Any	Any	
	Hunter	No	No	Yes	No	No	Yes	No	No	No	Any	Any	
	Cox & Slepian	No	No	No	No	Yes	No	Yes	No	No	One	Erroneously	Approximate attenuation
	Fortescue, Atherton, & Cox	No	No	No	No	Yes	No	Yes	No	On one span	One	Erroneously	Approx. for the mutual induction
	Ideal ground wires (this paper)	Yes	Yes	Yes	Yes	Yes	Hunter's	No	No	No	Any	Any	
	Periodic resistance grounds (This paper)	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Any	Any	
TESTS	On Models—Peek	No	Yes	Yes	No	No	Yes	No	No	No	Any	Any	
	Antennas	No	Yes	Yes	No	No	Yes	Yes	No	No	One	One	Unsatisfactory
	Traveling Waves—McEachron	No	No	No	No	Yes	Yes	Yes	Partly	Partly	Any	Any	Equal waves on all wires

charge, the distribution of bound charge, the formation and development of traveling waves, and residual charges. It is applicable to systems having any number of ground and line wires, and Hunter's correction for the effects of corona can be applied in the same way as to the conventional method of calculation.

Now the amazing conclusion reached as a result of this analysis is that the protective ratio (in the case of ideal ground wires) is independent of the law of cloud discharge, of the distribution of bound charges, and of traveling waves, and is exactly the same expression as that found by the conventional method of calculation. In other words, the same protective ratio would be found by any method for which ideal ground wire conditions prevail, and these include:

1. The conventional method (and Hunter's correction).
2. Tests on model transmission lines (Peek).
3. Tests with traveling waves (McEachron).
4. Measurements on antennas.

Of course, the actual voltages induced on a line are quite different, depending on the law of cloud discharge, etc., but the *percentage* reduction in voltage to be realized by the employment of ground wires is independent of these factors.

Appendix II, therefore, establishes the validity for obtaining the protective ratio by any of the several different methods. In addition, Appendix II offers a means for computing the actual voltage induced on a line. It may appear academic to talk about ideal ground wire conditions, but as a matter of fact, such conditions substantially obtain at the tower within a fraction of a microsecond after the start of cloud discharge (the time that it takes a wave to travel twice the height of the tower). Out in mid span, one or two microseconds may pass before ideal ground wire conditions prevail. Also, as McEachron, Hemstreet, and Rudge[6] have found experimentally, and as was verified by calculations in this paper, a ground resistance of the order of 75 ohms provides nearly 95 per cent of the protection possible with perfect grounds. And finally, the fronts of waves caused by induced potentials are not abrupt, so that the negative reflections traveling back from the grounding points at the towers arrive before maximum potential occurs and thereby, in effect, the ground wires function as ideal ground wires. Nevertheless, it is deemed advisable to present a general treatment of periodic resistance grounds, in order to prove these contentions.

Periodic Resistance Grounds. The essential elements of the theory of periodic resistance grounds have already been given by Cox and Slepian.[2] It remains to extend the theory to include the effects of the law of cloud discharge, of the distribution of bound charge and of a multiplicity of reflections from successive spans, and to take into account properly the presence of any number of line and ground wires. The generalization will then be complete.

In a previous paper[1] the author derived three different methods (graphical, tabular, and analytic) for calculating the shape of traveling waves induced by lightning in terms of the functions $F(t)$ and $f(x)$ representing the law of cloud discharge and the initial distribution of bound charge respectively. It was there shown that

the shape of the traveling wave is changing during the cloud discharge. This may be called the formation period, to distinguish it from the period following the completion of cloud discharge when the waves are fully developed and suffer no further change in shape except the attenuation and distortion due to losses. However, that part of a forming wave which has moved beyond the region occupied by the bound charge is the same as the corresponding part of the fully developed wave. It is therefore possible to specify the shape of wave issuing from a bound charge distribution as proportional to some function $\phi(t)$ involving $F(t)$ and $f(x)$, and this function may be discovered by any of the three methods given in the bibliography. In particular, the function $f(x)$ may be considered to be only that part of a total bound charge distribution which lies between adjacent towers, and then the simultaneous effect of all spans included by the bound charge can be found by superposition.

In Appendix I of this paper, the theory of traveling waves on any number of mutually coupled parallel wires is worked out, and the behavior of these waves at rather general transition points is specified. The solution obtained applies to Fig. 3 and from it the special cases shown in Fig. 4 have been given as simple examples of its application. Fig. 4f may be taken as a resistance ground on one ground wire protecting one line wire. But it is shown in Appendix III that each line wire behaves independently of the others; and according to Equations (38) to (42) of Appendix I it is possible to lump all the ground wires as a single equivalent ground wire if they are all at the same height above ground, that is, all carrying equi-potential waves. If all ground wires are not at the same potential, then as an approximation, this replacement may be effected by an equivalent ground wire at their average potential. In practical cases the error is negligible, and avoids the complication of including mutual connection links at the transition points of Fig. 3.

Hereby, without loss of essential generality, Fig. 4f contains all of the elements entering into the analysis, and the effect of a wave striking the resistance junction is given by Equations (3), (4), (5), and (6) of Appendix III. Finally, the simultaneous existence of waves on different spans, and the multiplicity of reflections and refractions to which they give rise, may be taken into account through the use of the lattice indicated in Fig. 5. The theory of such lattices is given in Appendix III.

The steps in the complete solution are then as follows:

(A) Replace the actual ground wires by an equivalent ground wire, consistent with the conditions imposed by Equations (38) to (41), Appendix I.

(B) Consider each span between towers separately, and for each span compute the traveling waves on every wire. Then

$f_1 = \phi(t) \, . \, h_1 G$ = *incident wave on ground wire.*

$f_2 = \phi(t) \, . \, h_2 G$ = *incident wave on line wire.*

where h_1 and h_2 are the heights of the wires, G is the field gradient, and $\phi(t)$ is a function involving the bound charge distribution $f(x)$ on the span and the law of cloud discharge $F(t)$. It may be evaluated by any of the graphical, tabular, or analytic methods given in the bibliography.[1] It is simply the function expressing the shape of the wave issuing from the bound charge distribution.

(C) Calculate the reflection and refraction operators for both the line and ground wires as given by Equations (3), (4), (5), and (6) of Appendix III. Then

$F_1 = a f_1$ = *reflected wave on ground wire*

$f_1'' = b f_1$ = *transmitted wave on ground wire*

$F_2 = c f_1$ = *reflected wave on line wire*

$f_2'' = f_2 + c f_1$ = *transmitted wave on line wire.*

(D) Construct a lattice as shown in Fig. 5 of a sufficient number of sections to include the requisite time interval and number of spans, and therefrom

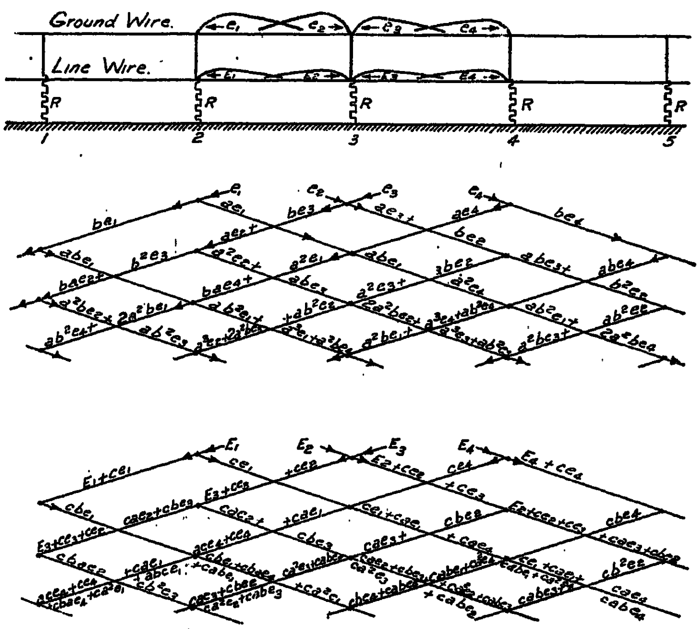

FIG. 5—WAVES FROM RELEASED BOUND CHARGES

Top lattice: Reflections and refractions on ground wire
Bottom lattice: Reflections and refractions on line wire

determine the potentials at all points by superposition.

The most simple case is that of instantaneous cloud discharge and rectangular bound charges. This also gives the maximum departure of the potential at mid-span with respect to that at the tower. Curves calculated on this assumption for a bound charge 2,000 ft. long and 1,000 ft. spans are shown in Fig. 6. They differ from those shown by Fortescue, Atherton, and Cox[3] in being based on different constants and in taking into account all reflections up to the included time interval. The traveling wave on the line wire is 0.550 (18 per cent high), 0.488 (4 per cent high), and 0.472 (1 per cent high) after zero, one, and two microseconds respectively. Potential differences between line and ground wires greater than these values (1.30 maximum for one-half a microsecond) are limited to the two spans which held the bound charge. These excess potentials

diminish in importance as the rate of cloud discharge decreases. Had the ground wires been ideal, the voltage on the line wire would have been 0.467.

II. Direct Hits

Investigations of direct hits on lines fall into two categories. First, there are the statistical studies relating to the probability of a lines being struck and the magnitudes involved, and second, there is the analysis of the resulting disturbances.

In Fig. 7a is shown a transmission line tower situated on a level plane free of brush or other projections. While the idiosyncrasies of a lightning bolt are too erratic for one to predict where it will go, yet the only justifiable assumption is to suppose that on an average

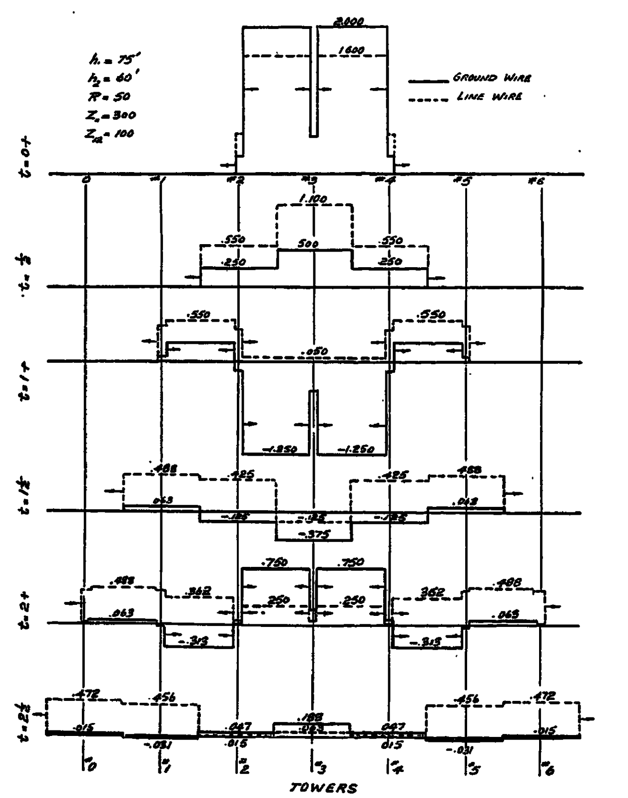

Fig. 6—Approach to Ideal Ground Wire Conditions on the Spans

it will strike to the nearest object. On this basis, the stroke will, by preference, hit the tower when the distance r is less than the height H. In Fig. 7b are plotted a set of curves showing the distance D, corresponding to $r = H$, between the projection of the approaching center of disturbance and the tower, as a function of the cloud height H and the tower height h. If there is absolute certainty that lightning will strike within a zone of width W centered on the transmission line, then the probability that the line will receive the stroke is $2\,D/W$. When it is realized from the curves of Fig. 7b that the susceptible zone $2\,D$ is of the order of 1,000 ft. it is not surprising that lines are hit. If the tower is on the top of a hill or ridge (as is so often the case in order to provide for long spans) then the chance of being hit is greatly magnified. The susceptible distance $2\,D$ can only be ascertained in such a case by drawing the clearance arc as shown in Fig. 7c. The tower is more likely to be struck than the span, because it is higher than the sagging span, and also because the towers usually occupy the high points along the right of way.

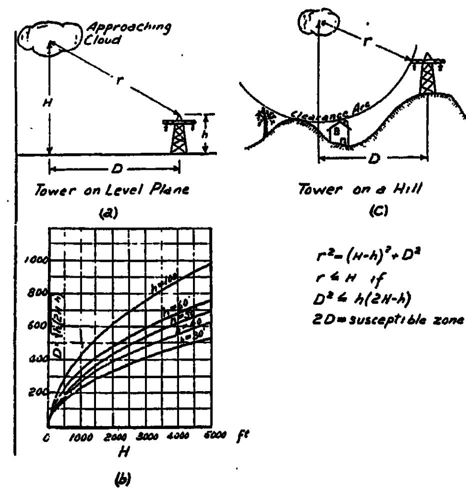

Fig. 7—Probability of a Line Being Hit

It has been proposed to provide line towers with extension masts of sufficient height to insure their being struck instead of any part of the line. The necessary height of such masts is of the order of 200 ft. for line heights of the order of 60 ft. and spans 1,000 ft. long. Still other schemes have been advanced, such as paralleling the transmission line by separate masts supporting a direct hit wire, etc. Of course any scheme that is used must have economic justification.

It is of interest to speculate on the maximum voltage of a direct hit. Lightning waves measured on transmission lines by cathode-ray oscillograph stations have been from 10 to 200 microseconds in length, thus showing that the cloud discharge has persisted long enough to establish equilibrium conditions in the lightning bolt itself (that is, successive reflections, if they actually occur, will have subsided). Thereafter,

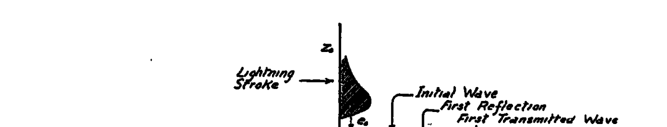

Fig. 8—Reflected and Transmitted Waves Due to Periodic Resistance Grounding

the potential drop along the lightning bolt is probably uniform. Now for a steady impulse lasting 10 microseconds or longer, the flashover voltage in air is from 150 to 200 kv./ft., so that a line wire 60 ft. high on wood poles could not support a voltage much in excess of 10×10^6 volts without a side flash to ground occurring.

If a side flash does take place, then the voltage on the line would be 60 G, where G is the gradient along the stroke, and if uniform, does not greatly exceed 100 kv./ft. Therefore, the maximum voltage on a 60-ft. line is probably of the order of 10×10^6 volts.

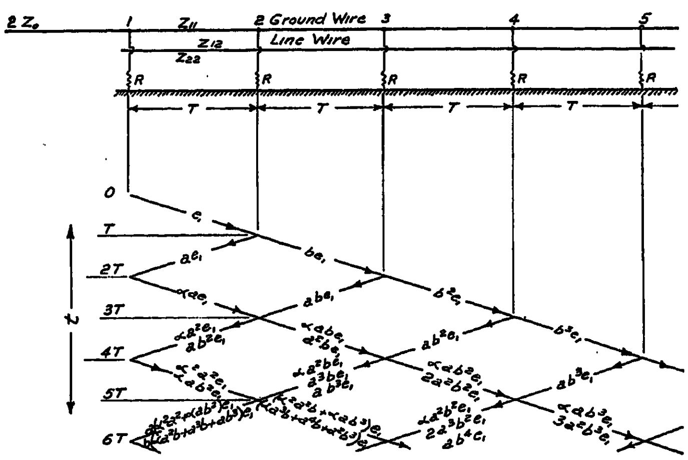

FIG. 9—REFLECTIONS AND REFRACTIONS ON GROUND WIRE. LIGHTNING STROKE AT TOWER

The voltages on the ground wire at the junctions as functions of time are:

$$e_1 = e_1(t) + [a + \alpha a] \cdot e_1(t - 2T) + [(1 + \alpha)(\alpha a^2 + a b^2)] \cdot e_1(t - 4T) + \ldots$$

$$e_2 = b e_1(t - T) + [a b + a^2 b + \alpha a b] \cdot e_1(t - 3T) + \ldots$$

$$e_3 = b^2 e_1(t - 2T) + [a b^2 + 2 a^2 b^2 + \alpha a b^2) \cdot e_1(t - 4T) + \ldots$$

$$e_4 = b^3 e_1(t - 3T) + \ldots$$

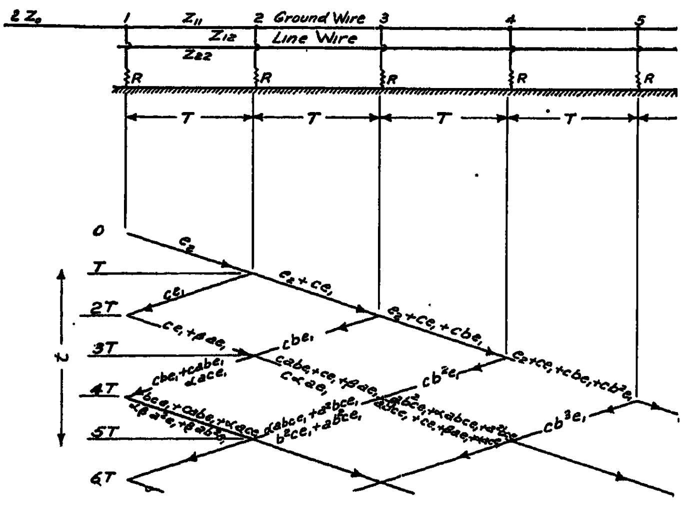

FIG. 10—REFLECTIONS AND REFRACTIONS ON LINE WIRE. LIGHTNING STROKE AT TOWER

The voltages on the line wire at the junctions as functions of time are:

$$E_1 = e_2(t) + [2c + \beta a] \cdot e_1(t - 2T) + [2bc + 2abc + 2\alpha a c + \alpha\beta a^2 + \beta a b^2] \cdot e_1(t - 4T) + \ldots$$

$$E_2 = e_2(t - T) + c e_1(t - T) + [c + \beta a + bc + abc + \alpha a c] \cdot e_1(t - 3T) + \ldots$$

$$E_3 = e_2(t - 2T) + [c + bc] \cdot e_1(t - 2T) + [b^2 c + a b^2 c + \alpha a b c + a^2 b c + abc + c + \beta a + \alpha a c] \cdot e_1(t - 4T) + \ldots$$

$$E_4 = e_2(t - 3T) + [c + bc + b^2 c] \cdot e_1(t - 3T) + \ldots$$

Currents in the tower of the order of 100,000 amperes have been indicated by the direct hit recorder.[9] If these currents were due to a direct hit at the tower of resistance R, then the voltage across the tower was 100,000 R. By Equation (7) of Appendix III this corresponds to a lightning voltage of

$$e_o = \left\{ \frac{Z_{11}(R + Z_o) + 2 R Z_o}{2 Z_{11}} \right\} 100{,}000$$

which, in the case of two ground wires, gives a range of $e_o = 10 \times 10^6$ to $e_o = 20 \times 10^6$ corresponding to $O < R < 100$ ohms, and an assumed surge impedance of $Z_o = 200$ for the lightning bolt. On the other hand,

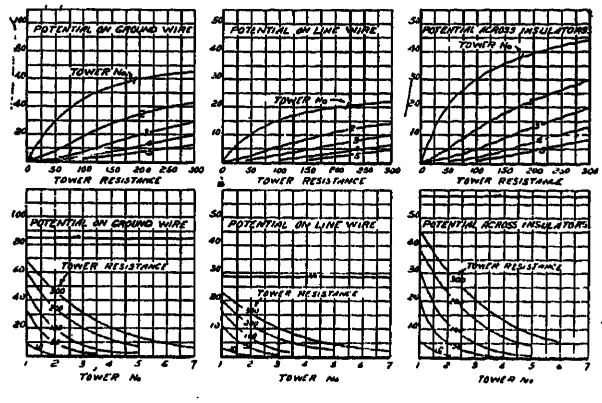

FIG. 11—POTENTIALS AT THE TOWERS IN PER CENT OF THE LIGHTNING VOLTAGE

if the 100,000 amperes was a result of a direct hit at mid span there is a possibility of there being double these voltages in the lightning stroke.

Fig. 11 illustrates the effect of resistance on the ground and line wire potentials, and the difference in potential between line and ground wires. These curves are based on the equations and lattices described in Appendix III and were prepared in imitation of those previously given by Fortescue, Atherton, and Cox.[3]

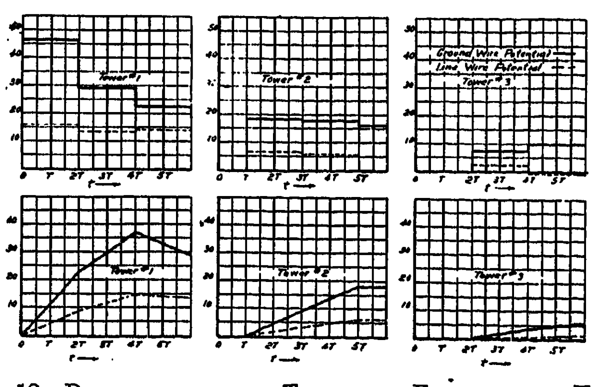

FIG. 12—POTENTIALS AT THE TOWERS AS FUNCTIONS OF TIME

Top: Infinite rectangular applied wave
Bottom: Infinite flat-top wave with 4 T front

Fig. 12 shows the voltages as functions of time at three adjacent towers, and includes the effects of successive reflections from all adjacent towers.

In general, there are four distinct and definite advantages to low ground resistances:

1. Reduced potential on the ground wires at the tower.

2. Reduced potential on the line wires at the tower.

3. Reduced potential between line and ground wires.
4. Limitation of dangerous potentials to fewer spans.

Low ground resistance is obtained by decreasing the tower footing resistance and by the installation of counterpoises. The proper disposition and arrangement of counterpoises appears at present to be a matter of test rather than of calculation.

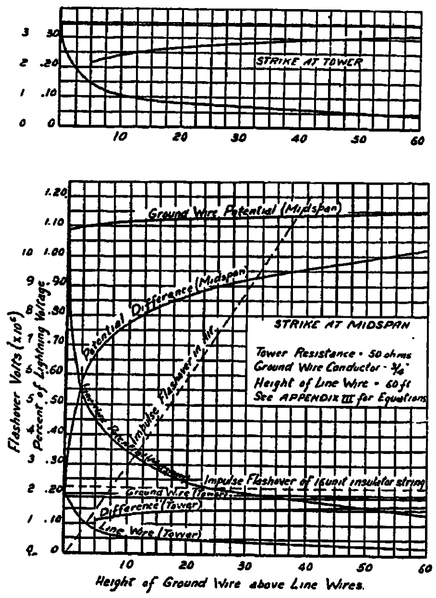

FIG. 13—EFFECT OF INCREASING THE HEIGHT OF THE GROUND WIRE

Induced potentials, co-existing with those due to the direct stroke, alleviate the magnitude of the impressed voltages, for the induced voltages are opposite in sign to those caused by the direct strokes. Referring to Fig. 14, let capital letters represent the voltages of the direct stroke, and small letters the induced voltages. Then

$$E_2 - e_2 = \frac{(Z_{12})}{(Z_{11})} E_1 - e_2 = \text{voltage on line wire}$$

$$E_1 - e_1 = \text{voltage on ground wire}$$

$$E_1 \left(1 - \frac{Z_{12}}{Z_{11}}\right) - (e_1 - e_2) = \text{voltage between wires.}$$

Now since the ground wire is usually higher than the line wire, its induced potential is greater, so that

$$e = (e_1 - e_2) = \text{a positive quantity}$$

Therefore, the presence of the induced potential reduces the voltage between wires by e, and to a much greater extent reduces the voltages on both line and ground wires. Direct stroke calculations which neglect the induced charges are consequently pessimistic and err on the safe side.

Peek has advocated the use of one ground wire, called the direct-hit wire, sufficiently higher than the other conductors so that they will fall inside its protective wedge. Other ground wires may be used in conjunction with it to limit the potentials caused by induced strokes. Unless the direct-hit wire is placed sufficiently high such an arrangement does not obviate the possibility of side flashes taking place from the direct-hit wire to the other conductors. Nor is it an unmitigated advantage to increase the height of the direct-hit wire beyond that necessary to avoid side flashes, for a higher wire not only invites more strikes, but also increases the voltage between the line and ground wires, so that the potential across the insulator string is increased. Curves illustrating these conditions are shown in Fig. 13 for strikes at the tower and at midspan. The basis of comparison is the lightning voltage, defined as the potential of a hypothetical freely traveling wave descending the lightning bolt of surge impedance Z_o. The method of analysis is described in Appendix III. Two scales for the ordinates have been given in Fig. 13, a percentage scale which is valid for all lightning voltages, and a voltage scale based on a lightning voltage of 10×10^6 volts. This is probably as severe a stroke as it would be feasible to design for.

In designing a line for a maximum lightning voltage of 10×10^6 it is evident from Fig. 13 that the direct hit wire must be elevated 35 ft. above the line wires at midspan to insure that there will be no side flash to them. The requisite number of insulators at the towers depends upon the ground resistance and may be decreased when good grounds are obtained, or else carry a greater margin of safety. Fig. 13 shows curves corresponding to a ground resistance of 50 ohms. Too much emphasis cannot be laid on the advantage of decreasing the tower resistance, as was illustrated in Fig. 11. For resistances of the order of 10 ohms the reduction in voltage is practically proportional to the tower resistance, that is, a 5-ohm tower resistance means only half the voltage of a 10-ohm tower resistance.

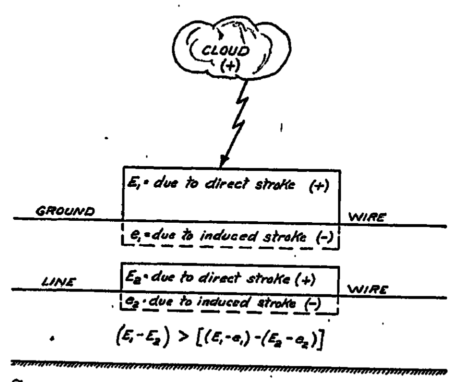

FIG. 14—SUPERPOSITION OF DIRECT STROKE AND INDUCED POTENTIALS

III. OTHER EFFECTS

While ground wires are used primarily as protection against induced and direct strokes, yet they exert a number of interesting subsidiary effects, such as influence on attenuation, telephone interference, corona loss, and zero phase sequence reactance. Some of these effects will be discussed here in a superficial sort of way but with no pretense at completeness.

Effect of Ground Wires on Wave Propagation. The history of a traveling wave is described in terms of three characteristics: (1) velocity of propagation, (2) distortion, and (3) attenuation. The introduction of ground wires does not change the velocity of propagation of waves on a transmission line, except for the negligible influence of that part inside the conductor of the total magnetic field linking the ground wire. For steep short waves, such as are caused by lightning, the transient skin effect is sufficiently high so as to practically exclude the internal fields of self-induction, and even when the current is uniformly distributed, the contribution of the internal field is negligible for high-tension transmission line spacings. Wave distortion is affected in two different ways by the presence of ground wires: first, the losses due to corona and skin effect experienced by that part of the energy transferred to the ground wires; and second, the superposition of high-frequency oscillations caused by successive reflections between towers. If the grounding resistances of the towers are low, then these oscillations are not perceptible, but for high tower resistances they become noticeable in the waves on the line conductors, by mutual induction from the ground wires. In the attenuation tests described by McEachron, Hemstreet, and Rudge,[6] it was found that the attenuation of positive surges was not affected by the presence of ground wires, but that negative surges attenuated less rapidly. They show, as a result of this decreased attenuation, the interesting possibility, in the case of inefficient ground wires, of a surge originating out on the line and arriving at the station with a greater amplitude than it would have had if there were no ground wires, although the surge was reduced by the presence of ground wires at the point of origin.

Introduction of Extra Ground Wires. Some power systems follow a policy of introducing extra ground wires over a short section (from a few hundred feet to a mile or more) adjacent to the station. The benefit derived from these extra ground wires is material for surges originating on the same section. However, the decrease in effective surge impedance due to the introduction of extra ground wires is small, and to reduce an incoming surge by more than a few per cent requires several advantageously placed ground wires. This is the so-called "second effect" of a ground wire, Fig. 4b, and is computed according to Case III, Appendix I. The extra ground wires should extend out from the station sufficiently far, so that surges originating beyond them will have been reduced below the dangerous value by attenuation. High potential lightning waves attenuate very rapidly, approximately to half value in one or two miles, so that the extra ground wires should extend far enough beyond the station to take requisite advantage of such attenuation.

Effect on Telephone Interference. A completely transposed three-phase transmission line with isolated neutral will not induce voltages in an adjacent telephone circuit. But if the neutral is grounded, zero phase sequence currents and the third harmonic current and its multiples are permitted to flow in phase in the line conductors and return through the ground connections, and these currents induce voltages in the neighboring telephone circuit. If there are ground wires present, the currents induced in them by the third harmonic line currents affect the telephone circuit. The amount may be computed by means of Equations (7), Appendix I. Let conductors $(1, 2, \ldots m)$ be ground wires and conductors $(m + 1, \ldots, n)$ the line wires. Then if resistance is negligible there must be

$$\phi_1 = \phi_2 = \ldots\ldots = \phi_m = 0$$

so that, upon rearrangement, the first m equations of Equation (7) became

$$\left.\begin{array}{l} L_{11}\, i_1 + \ldots\ldots + L_{m1}\, i_m \\ \qquad = -\, [L_{(m+1)1}\, i_{(m+1)} + \ldots\ldots + L_{n1}\, i_n] \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ L_{1m}\, i_1 + \ldots\ldots + L_{mm}\, i_m \\ \qquad = -\, [L_{(m+1)m}\, i_{(m+1)} + \ldots\ldots + L_{nm}\, i_n] \end{array}\right\}$$

from which the m ground wire currents may be determined in terms of the $(n - m)$ known line currents. Having found the ground wire currents, the voltage induced in a telephone circuit x is

$$e_x = -\frac{\partial \phi_x}{\partial t} = -\frac{\partial}{\partial t}[L_{1x}\, i_1 + \ldots\ldots + L_{nx}\, i_n]$$

This result is not limited to a transposed line, nor to the third harmonic currents, but is general within the limitations of no losses in the conductors. However, the inductance coefficients cannot be calculated on the basis of the zero equipotential surface being at the ground surface. It is usually several thousand feet below the surface, depending upon soil conditions.

As a specific example, consider a completely transposed three-phase line with two ground wires. Then

$$L_{11}\, i_1 + L_{21}\, i_2 = -\,(L_{31}\, i_3 + L_{41}\, i_4 + L_{51}\, i_5)$$
$$L_{12}\, i_1 + L_{22}\, i_2 = -\,(L_{32}\, i_3 + L_{42}\, i_4 + L_{52}\, i_5)$$

But for a completely transposed line

$L_{31} = L_{41} = L_{51}$

$L_{32} = L_{42} = L_{52}$

$I = i_3 + i_4 + i_5 =$ *total 3rd harmonic current in line wires.*

Then

$$i_1 = \frac{L_{23}\, L_{12} - L_{22}\, L_{13}}{L_{11}\, L_{22} - L_{12}^2}\, I$$

$$i_2 = \frac{L_{12}\, L_{13} - L_{11}\, L_{23}}{L_{11}\, L_{22} - L_{12}^2}\, I$$

and the voltage induced in the telephone circuit is

$$e_x = -\frac{\partial}{\partial t}[L_{1x}\, i_1 + L_{2x}\, i_2 + L_{3x}\, I]$$

$$= \left[\frac{L_{1x}(L_{22}L_{13} - L_{12}L_{23}) + L_{2x}(L_{11}L_{23} - L_{12}L_{13})}{(L_{11}L_{22} - L_{12}^2)} - L_{3x} \right] \frac{\partial I}{\partial t}$$

Zero Phase Sequence Reactance. The zero phase sequence reactance of a transmission line is of importance in calculations of system stability[10] and ground fault currents. This reactance is considerably affected by the presence of ground wires. Its determination is exactly the same kind of a problem as given in the previous section on telephone interference. Numbering the first m conductors as ground wires and the remaining $(n - m)$ conductors as line wires, there is

$$\phi_1 = \phi_2 = \ldots\ldots\ldots\ldots = \phi_m = 0$$

since the ground wires are at zero potential. For a completely transposed line, the zero phase sequence currents are

$$i_{(m+1)} = \ldots\ldots\ldots\ldots = i_n = i_o$$

and therefore

$$\left.\begin{array}{l} L_{11}i_1 + \ldots + L_{m1}i_m = -[L_{(m+1)1} + \ldots + L_{n1}]\,i_o \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ L_{1m}i_1 + \ldots + L_{mm}i_m = -[L_{(m+1)m} + \ldots + L_{nm}]\,i_o \end{array}\right\}$$

From these m simultaneous equations the m ground wire currents $(i_1 \ldots i_m)$ may be found. Then the flux linkages of the line wires are

$$\left.\begin{array}{l} \phi_{(m+1)} = L_{1(m+1)}i_1 + \ldots\ldots + L_{n(m+1)}i_n \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ \phi_n = L_{1n}i_1 + \ldots\ldots + L_{nn}i_n \end{array}\right\}$$

and the zero phase sequence reactance is then defined as

$$X_o = 2\pi f \quad L_o = 2\pi f \left[\frac{\phi_{(m+1)} + \ldots\ldots + \phi_n}{(n - m)\,i_o} \right]$$

Effect on Corona. The presence of ground wires may influence the gradients on the line conductors due to the normal system voltage, and may thereby change the critical disruptive corona voltage and the corresponding losses. Peek's equation for the corona loss[4] per mile per wire is

$$P = \frac{390}{\delta}(f + 25)\sqrt{\frac{r}{s}}\,(e - e_o)^2\,10^{-5}\text{ kw.}$$

and the critical disruptive corona gradient is

$$g_o = 53.4\,m_o\,\delta = \frac{2\,Q}{r}$$

where m_o is the roughness factor, δ is the air density factor, and Q is the charge on the conductor of radius r.

Now in the case of n wires of which the ground wires are numbered from No. 1 to No. m inclusive, the system of charges may be solved for from Equation (1), Appendix I in terms of the potentials on the conductors. Since the potentials on the ground wires are all zero, there is

$$\left\{\begin{array}{l} 0 = p_{11}Q_1 + \ldots\ldots\ldots + p_{n1}Q_n \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ 0 = p_{1m}Q_1 + \ldots\ldots\ldots + p_{nm}Q_n \\ V_{(m+1)} = p_{1(m+1)}Q_1 + \ldots\ldots + p_{n(m+1)}Q_n \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ V_n = p_{1n}Q_1 + \ldots\ldots\ldots + p_{nn}Q_n \end{array}\right.$$

The voltages to ground $(V_{(m+1)} \ldots\ldots V_n)$ for a balanced polyphase circuit have the same amplitude V, so that the solution for any Q in the above n simultaneous equations ultimately reduces to

$$Q = V \cdot \phi\,(p)$$

where $\phi\,(p)$ is the function of the $(p$'s) occurring in the solution. The critical disruptive corona voltage is then that voltage for which

$$g_o = 53.4\,m_o\,\delta = \frac{2\,Q}{r} = 2\,V\frac{\phi\,(p)}{r}, \text{ or}$$

$$V = 26.7\,m_o\,\delta\frac{r}{\phi\,(p)} = e_o$$

The factor $\sqrt{r/s}$ appearing in the power equation is of empirical origin. In the absence of experimental data as to the best interpretation to place on this factor in the case of more than two wires, it is advisable to use s as the distance to the nearest adjacent conductor.

As an example, consider a three-phase circuit with one ground wire, as in the first arrangement of Table I. Suppose that the line and ground wires are all 0.75 in. diameter, with 10 ft. spacing, and the line conductors 50 ft. above the ground level. Then it is easily verified that

$p_{11} = 16.50$	$p_{12} = 4.06$	$p_{23} = 4.61$
$p_{22} = 16.13$	$p_{13} = 4.80$	$p_{24} = 3.26$
$p_{33} = 16.13$	$p_{14} = 4.06$	$p_{34} = 4.61$
$p_{44} = 16.13$		

and the solution of the four simultaneous equations gives for the charge on the middle line conductors

$$Q_3 = 0.0883\,V$$

Then the critical disruptive corona voltage is

$$V = e_o = 26.7\,m_o\,\delta\frac{.375}{0895} = 112\,m_o\,\delta\text{ kv.}$$

Had the ground wire been neglected it would have been

$$e_o = 113.5\,m_o\,\delta$$

Incidentally, if only adjacent line conductors are taken

$$e_o = 114\,m_o$$

Of course one should not generalize from this single set of calculations, but every important installation should be calculated completely.

Appendix I

MAXWELL'S ELECTROSTATIC COEFFICIENTS

Consider a system of n conductors of any shape and arrangement, fixed in position and uncharged. If a

unit charge be placed on conductor x suppose that the potentials acquired by the conductors are $(p_{x1}, p_{x2}, \ldots, p_{xx}, \ldots, p_{xn})$. Had a charge Q_x been placed on conductor x, instead of unit charge, the potentials would have been Q_x times as large, or $(Q_x p_{x1}, \ldots, Q_x p_{xn})$. In this notation the first subscript denotes the conductor on which the charge was placed (in this case x), and the second subscript the conductor taking that potential. It follows by the principle of superposition that the effect of simultaneous charges $(Q_1, Q_2, \ldots, Q_n)$ on all the n conductors is to give rise to the system of potentials

$$\left.\begin{array}{l} V_1 = p_{11} Q_1 + p_{21} Q_2 + \ldots\ldots\ldots + p_{n1} Q_n \\ V_2 = p_{12} Q_1 + p_{22} Q_2 + \ldots\ldots\ldots + p_{n2} Q_n \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ V_n = p_{1n} Q_1 + p_{2n} Q_2 + \ldots\ldots\ldots + p_{nn} Q_n \end{array}\right\} \quad (1)$$

The above equations give the potentials in terms of the charges and the coefficients p. These linear coefficients of proportionality depend only on the geometrical properties of the conductors, as their size, shape, and position. In a few simple cases, such as parallel cylinders, they can be calculated, but in most cases must be determined experimentally.

Solving Equation (1) for the charge Q_x on conductor x, there is

$$Q_x = K_{x1} V_1 + K_{x2} V_2 + K_{x3} V_3 + \ldots + K_{xn} V_n \quad (2)$$

where $D\,K_{xy}$ is the minor of which p_{xy} is the co-factor in the expansion of

$$D = \begin{vmatrix} p_{11}\, p_{21} \ldots\ldots p_{n1} \\ p_{12}\, p_{22} \ldots\ldots p_{n2} \\ \ldots\ldots\ldots\ldots\ldots \\ p_{1n}\, p_{2n} \ldots\ldots p_{nn} \end{vmatrix} \quad (3)$$

To show that all of the potential coefficients p are positive, suppose that $Q_1 = +1$ and $Q_2 = Q_3 = \ldots = Q_n = 0$. Then V_1 is the greatest potential in the field, and the potentials of the other conductors must lie intermediate between V_1 and zero, hence all positive. If $V_1 = +1$ and $V_2 = V_3 = \ldots = V_n = 0$, then it is evident that $K_{11} = Q_{11}$ is positive and K_{12}, K_{23}, etc., are all negative, since the lines from Q_{11} must terminate either at infinity or on the other conductors. Therefore K_{xy} is negative if $x \neq y$. By means of Green's reciprocal theorem (see "Electricity and Magnetism" by J. H. Jeans, p. 92) it may be shown that $p_{xy} = p_{yx}$ and therefore $K_{xy} = K_{yx}$. Recapitulating,

$$\left.\begin{array}{l} p_{xy} = p_{yx} \text{ and } K_{xy} = K_{yx} \\ p_{xy}, K_{xx} \text{ are positive} \\ K_{xy} \text{ is negative if } x \neq y \end{array}\right\} \quad (4)$$

Now consider a system of parallel cylindrical conductors of sufficient length so that end effects are negligible, and whose spacings are large compared to their radii. If these conductors are over a zero potential plane, as shown in Fig. 15, then the method of images may be applied and from electrostatics there is

$$p_{xx} = 2 \log \frac{2h}{r} \times 9 \times 10^{11} \text{ daraf per cm.} \quad (5)$$

$$p_{xy} = 2 \log \frac{a}{b} \times 9 \times 10^{11} \text{ daraf per cm.} \quad (6)$$

where

r = radius of conductor x
h = height of conductor x above the zero potential plane
a = distance between x and the image of y
b = distance between x and y

Maxwell's Electromagnetic Coefficients

If in a system of n conductors carrying currents, and free from saturation effects, the flux linkages of conductor x due to its own current i_x is $(L_{xx} i_x)$ and the flux linkages of conductor y due to the current i_x is $(L_{xy} i_x)$; then by the principle of superposition the total flux linkages for all conductors are

$$\left.\begin{array}{l} \phi_1 = L_{11} i_1 + L_{21} i_2 + \ldots\ldots L_{n1} i_n \\ \phi_2 = L_{12} i_1 + L_{22} i_2 + \ldots\ldots L_{n2} i_n \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ \phi_n = L_{1n} i_1 + L_{2n} i_2 + \ldots\ldots L_{nn} i_n \end{array}\right\} \quad (7)$$

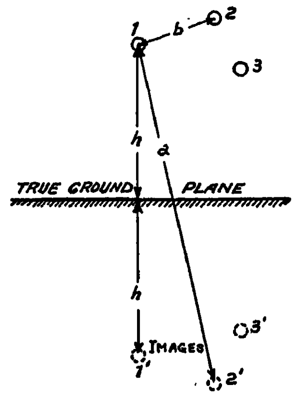

Fig. 15—System of Conductors and Their Images

From energy considerations (see "Electricity and Magnetism" by J. H. Jeans, p. 443) it may be shown that

$$L_{xy} = L_{yx} \quad (8)$$

For the system of parallel wires of Fig. 15

$$L_{xx} = \left(\frac{1}{2} + 2 \log \frac{2h}{r} \right) 10^{-9} \text{ henrys per cm.} \quad (9)$$

$$L_{xy} = \left(2 \log \frac{a}{b} \right) 10^{-9} \text{ henrys per cm.} \quad (10)$$

Self and Mutual Surge Impedances

Equations (2) and (7) apply to a system of parallel wires carrying currents above a zero potential plane, if the losses due to resistance, skin effect, leakage, and corona are ignored. If distance along the circuit is given by the coordinate x, then

$$-\frac{\partial i_1}{\partial x} = \frac{\partial Q_1}{\partial t} = K_{11}\frac{\partial e_1}{\partial t} + K_{12}\frac{\partial e_2}{\partial t} + \ldots\ldots + K_{1n}\frac{\partial e_n}{\partial t} \qquad (11)$$

$$-\frac{\partial e_1}{\partial x} = \frac{\partial \phi_1}{\partial t} = L_{11}\frac{\partial i_1}{\partial t} + L_{12}\frac{\partial i_2}{\partial t} + \ldots\ldots + L_{1n}\frac{\partial i_n}{\partial t} \qquad (12)$$

Differentiate (11) with respect to t and (12) with respect to x and substitute. Then

$$\begin{aligned}\frac{\partial^2 e_1}{\partial x^2} &= \frac{\partial^2}{\partial t^2}\{L_{11}(K_{11}e_1 + K_{12}e_2 + \ldots\ldots + K_{1n}e_n)\\ &\quad + L_{12}(K_{21}e_1 + K_{22}e_2 + \ldots\ldots + K_{2n}e_n)\\ &\quad \ldots\ldots\ldots\ldots\ldots\ldots\\ &\quad + L_{1n}(K_{n1}e_1 + K_{n2}e_2 + \ldots\ldots + K_{nn}e_n)\}\\ &= \frac{\partial^2}{\partial t^2}\{(L_{11}K_{11} + L_{12}K_{21} + \ldots\ldots + L_{1n}K_{n1})e_1\\ &\quad + (L_{11}K_{12} + L_{12}K_{22} + \ldots\ldots + L_{1n}K_{n2})e_2\\ &\quad \ldots\ldots\ldots\ldots\ldots\ldots\\ &\quad + (L_{11}K_{1n} + L_{12}K_{2n} + \ldots\ldots + L_{1n}K_{nn})e_n\}\\ &= \frac{\partial^2}{\partial t^2}\{J_{11}e_1 + J_{12}e_2 + \ldots\ldots + J_{1n}e_n\} \qquad (13)\end{aligned}$$

where

$$\begin{aligned}J_{rs} &= L_{r1}K_{1s} + L_{r2}K_{2s} + L_{r3}K_{3s} + \ldots\ldots + L_{rn}K_{ns}\\ &= L_{1r}K_{1s} + L_{2r}K_{2s} + L_{3r}K_{3s} + \ldots\ldots + L_{nr}K_{ns}\end{aligned} \qquad (14)$$

In operational notation the n equations of type (13) may be written as

$$\left.\begin{aligned}0 &= A_{11}e_1 + J_{12}e_2 + \ldots\ldots + J_{1n}e_n\\ 0 &= J_{21}e_1 + A_{22}e_2 + \ldots\ldots + J_{2n}e_n\\ &\ldots\ldots\ldots\ldots\ldots\ldots\\ 0 &= J_{n1}e_1 + J_{n2}e_2 + \ldots\ldots + A_{nn}e_n\end{aligned}\right\} \qquad (15)$$

where the operator

$$A_{rr} = \left\{J_{rr} - \frac{\partial^2}{\partial x^2}\int\int dt\right\} \qquad (16)$$

In order that (15) may have a solution other than zero there must be

$$\begin{vmatrix}A_{11}\,J_{12}\ldots\ldots J_{1n}\\ J_{21}\,A_{22}\ldots\ldots J_{2n}\\ \ldots\ldots\ldots\ldots\\ J_{n1}\,J_{n2}\ldots\ldots A_{nn}\end{vmatrix} e = 0 \qquad (17)$$

Since this determinate is of order n, its expansion yields a polynomial of degree n in the operator

$$\beta = \frac{\partial^2}{\partial x^2}\int\int dt \qquad (18)$$

If the coefficients are designated by a's then

$$(a_n\beta^n + a_{n-1}\beta^{n-1} + \ldots\ldots + a_1\beta + a_o)\,e = 0 \qquad (19)$$

Now if e is assumed to be a wave, it is

$$e = f(x + v\,t) \qquad (20)$$

and substituting (20) in (19) there is

$$a_n v^{-2n} + a_{n-1}v^{-2(n-1)} + \ldots\ldots + a_1 v^{-2} + a_o = 0 \qquad (21)$$

which is a polynomial of degree n in (v^{-2}), and therefore there are $2\,n$ values for the velocity of propagation (n positive and n negative) which satisfy the conditions for wave motion. If

$$B_{rr} = (J_{rr} - v^{-2}) \qquad (22)$$

then the n values of (v^{-2}) are given by the determinate

$$\begin{vmatrix}B_{11}\,J_{12}\ldots\ldots J_{1n}\\ J_{21}\,B_{22}\ldots\ldots J_{2n}\\ \ldots\ldots\ldots\ldots\\ J_{n1}\,J_{n2}\ldots\ldots B_{nn}\end{vmatrix} = 0 \qquad (23)$$

These considerations show that, in general, there can exist simultaneously on each wire of n paralleled wires, n pairs of waves of different velocities of propagation, ($v_1, v_2, \ldots, v_n$) and each pair consists of a forward and reverse wave. Therefore

$$\begin{aligned}e_1 &= f_{11}(x - v_1 t) - F_{11}(x + v_1 t) + \ldots\ldots\\ &\quad + f_{1n}(x - v_n t) + F_{1n}(x + v_n t)\end{aligned} \qquad (24)$$

The current, from Equations (11) and (24), is

$$\begin{aligned}i_1 &= \frac{-\partial}{\partial t}\int(K_{11}e_1 + K_{12}e_2 + \ldots\ldots + K_{1n}e_n)\,dx\\ &= K_{11}\Sigma v_r(f_{1r} - F_{1r}) + K_{12}\Sigma v_r(f_{2r} - F_{r2} + \ldots\ldots\\ &\quad + K_{1n}\Sigma v_r(f_{nr} - F_{nr})\end{aligned} \qquad (25)$$

where the summations include all of the waves in the expressions such as (24), for the potentials.

For traveling waves due to lightning, the transient skin effect is so high that the current is confined to a thin skin at the periphery of the conductor. Consequently there is no internal magnetic field, and the (1/2) factor in Equation (9) vanishes (it is due to the internal interlinkages on the assumption of uniform current distribution throughout the cross-section of the conductor). Then Equations (9) and (10) become

$$L_{xx} = 2\log\frac{2h}{r} \times 10^{-9} = \frac{p_{xx}}{c^2}\text{ henrys per cm.} \qquad (26)$$

$$L_{xy} = 2\log\frac{a}{b} \times 10^{-9} = \frac{p_{xy}}{c^2}\text{ henrys per cm.} \qquad (27)$$

$$c = (3 \times 10^{10})\text{ cm. per second} = \text{velocity of light} \qquad (28)$$

Substituting these values in Equation (14), there is

$$J_{rs} = c^{-2}(p_{1r}K_{1s} + p_{2r}K_{2s} + \ldots\ldots + p_{nr}K_{ns}) \qquad (29)$$

Referring back now to Equation (3), and remembering that $D\,K_{xy}$ is the minor, of which the cofactor is p_{xy}, in the expansion of D, it is evident that Equation (29) is that expansion if the elements of the r and s columns are identical. But in such a case a determinate vanishes. Therefore

$$J_{rs} = \begin{cases} 0 \text{ if } r \neq s \\ c^{-2} \text{ if } r = s \end{cases} \tag{30}$$

Under these conditions Equation (22) becomes

$$B_{rr} = (c^{-2} - v^{-2}) \tag{31}$$

and the determinate (23) degenerates to

$$\begin{vmatrix} B & 0 & \dots & 0 \\ 0 & B & \dots & 0 \\ \dots & & & \\ 0 & \dots & & B \end{vmatrix} = B^n = (c^{-2} - v^{-2})^n = 0 \tag{32}$$

Therefore $v = \pm c$, and all waves have the same velocity—that of light.

Hereby Equations (25) reduce to

$$\left.\begin{aligned} i_1 &= Y_{11}(f_1 - F_1) + Y_{12}(f_2 - F_2) + \dots + Y_{1n}(f_n - F_n) \\ i_2 &= Y_{21}(f_1 - F_1) + Y_{22}(f_2 - F_2) + \dots + Y_{2n}(f_n - F)_n \\ &\dots\dots\dots \\ i_n &= Y_{n1}(f_1 - F_1) + Y_{n2}(f_2 - F_2) + \dots + Y_{nn}(f_n - F_n) \end{aligned}\right\} \tag{33}$$

where

$$\left.\begin{aligned} Y_{rr} &= c\,K_{rr} = \text{self surge admittance} \\ Y_{rs} &= c\,K_{rs} = \text{mutual surge admittance} \end{aligned}\right\} \tag{34}$$

Inverting the order of solution which led to Equations (33) there are

$$\left.\begin{aligned} e_1 &= Z_{11}(g_1 - G_1) + Z_{21}(g_2 - G_2) + \dots + Z_{n1}(g_n - G_n) \\ e_2 &= Z_{12}(g_1 - G_1) + Z_{22}(g_2 - G_2) + \dots + Z_{n2}(g_n - G_n) \\ &\dots\dots\dots \\ e_n &= Z_{1n}(g_1 - G_1) + Z_{2n}(g_2 - G_2) + \dots + Z_{nn}(g_n - G_n) \end{aligned}\right\} \tag{35}$$

where

$$\left.\begin{aligned} Z_{rr} &= \frac{p_{rr}}{c} = 60 \log\left(\frac{2\,h}{r}\right) = \text{self surge impedance} \\ Z_{rs} &= \frac{p_{rs}}{c} = 60 \log\left(\frac{a}{b}\right) = \text{mutual surge impedance} \end{aligned}\right\} \tag{36}$$

$$\left.\begin{aligned} g &= g\,(x - v\,t) = \text{forward current wave} \\ G &= G\,(x + v\,t) = \text{reverse current wave} \end{aligned}\right\} \tag{37}$$

Suppose that a certain group of conductors, say $(n+1)$ to n inclusive, are carrying equal potential waves. Then it is possible, and usually convenient, to replace the effects of this group of wires by a single equivalent conductor. Let

$$f_o = f_{(m+1)} = \dots = f_n \tag{38}$$

$$i_o = i_{(m+1)} + \dots + i_n \tag{39}$$

$$Y_{ro} = Y_{r(m+1)} + \dots + Y_{rn} \tag{40}$$

$$Y_s = Y_{(m+1)s} + \dots + Y_{ns} \tag{41}$$

Then Equation (33) becomes

$$\left.\begin{aligned} i_1 &= Y_{11} f_1 + \dots + Y_{1m} f_m + Y_{1o} f_o \\ &\dots\dots\dots \\ i_m &= Y_{m1} f_1 + \dots + Y_{mm} f_m + Y_{mo} f_o \\ i_o &= Y_1 f_1 + \dots + Y_m f_m + Y_o f_o \end{aligned}\right\} \tag{42}$$

Hereby the number of equations has been reduced to $(m+1)$.

Behavior of Waves at a Transition Point

Suppose that each of the n conductors terminates at a transition point, as shown in Fig. 3, consisting of a lumped series impedance U, a lumped admittance to ground N, and outgoing lines fed through lumped series impedances W. In the general case U, N, W are operators involving circuit constants and time derivatives and integrals. The surge impedances of the outgoing lines are designated by small z, and those of the incoming lines by large Z. When incident waves $(f_1, \dots, f_n)$ traveling along the incoming lines reach the transition point, waves $(F_1, \dots, F_n)$ are reflected back onto the incoming lines, and refracted waves $(f_1'', \dots, f_n'')$ are transmitted to the outgoing wires, and currents $(I_1, \dots, I_n)$ flow to ground through the admittances $(N_1, \dots, N_n)$.

The total potential on the incoming line at the junction is

$$e_r + e_r' = f_r + F_r \tag{43}$$

and the total current, by Equation (33) is

$$i_r + i_r' = Y_{r1}(f_1 - F_1) + \dots + Y_{rn}(f_n - F_n) \tag{44}$$

The potential across the admittance N_r is

$$E_r = (e_r + e_r') - U_r\,(i_r + i_r') \tag{45}$$

so that the current through N_r is

$$I_r = N_r\,E_r \tag{46}$$

The current transmitted to the outgoing line is

$$i_r'' = y_{r1} f_1'' + y_{r2} f_2'' + \dots + y_{rn} f_n'' \tag{47}$$

The condition of current continuity requires that

$$i_r + i_r' = I_r + i_r'' \tag{48}$$

The potential transmitted to the outgoing line is

$$e_r'' = E_r - W_r\,i_r'' \tag{49}$$

Substituting (44), (45), (46), and (47) in (48), there is

$$\begin{aligned} (1 + N_r\,U_r)[Y_{r1}(f_1 - F_1) + \dots + Y_{rn}(f_n - F_n)] - N_r(f_r + F_r) \\ = (y_{r1} f_1'' + y_{r2} f_2'' + \dots + y_{rn} f_n'') \end{aligned} \tag{50}$$

Substituting (44), (45), (46), and (47), in (49), there is

$$\begin{aligned} (f_r + F_r) - U_r\,[Y_{r1}(f_1 - F_1) + \dots + Y_{rn}(f_n - F_n)] \\ = f_r'' + W_r\,(y_{r1} f_1'' + \dots + y_{rn} f_n'') \end{aligned} \tag{51}$$

Since r takes on all values from $r = 1$ to $r = n$ there are, n equations of type (50) and n equations of type (51), so that the $2\,n$ unknowns $(F_1 \dots F_n, f_1'' \dots f_n'')$ may be uniquely determined. A few simple examples will be worked out to show the application of Equations (50) and (51).

Case I. Find operational expressions for the reflected and transmitted waves when there is a single incoming wire and a single outgoing wire. Equations (50) and (51) then reduce to

$$(1 + N_1\,U_1)\,Y_{11}\,(f_1 - F_1) - N_1\,(f_1 + F_1) = y_{11} f_1''$$

$$-\,U_1\,Y_{11}\,(f_1 - F_1) + (f_1 + F_1) = f_1'' + W_1\,y_{11} f_1''$$

Solving these two equations simultaneously for the reflected wave F_1 and the refracted wave f_1'', substituting $z_{11} = 1/y_{11}$ and $Z_{11} = 1/Y_{11}$, and dropping subscripts, there is

$$F_1 = \frac{(z+W)(1+NU)+U-Z-ZN(z+W)}{(z+W)(1+NU)+U+Z+ZN(z+W)} f_1$$

$$f_1'' = \frac{2z}{(z+W)(1+NU)+U+Z+ZN(z+W)} f_1$$

For a large number of special cases to which these equations apply see *Traveling Waves Due to Lightning* by L. V. Bewley,[1] and *Shunt Resistors for Reactors* by F. H. Kierstead, H. L. Rorden, and L. V. Bewley, (A. I. E. E. TRANS., Vol. 49, July 1930).

Case II. A single wire entering a section consisting of a continuation and an adjacent isolated wire, Fig. 4c. There will be two transmitted waves, and one reflected wave. $U_1 = U_2 = W_1 = W_2 = N_1 = N_2 = 0$. Equations (**50**) and (**51**) give

$$Y_{11}(f_1 - F_1) = y_{11} f_1'' + y_{12} f_2''$$
$$0 = y_{21} f_1'' + y_{22} f_2''$$
$$(f_1 + F_1) = f_1''$$

Solving these three simultaneous equations and substituting impedances for admittances, there are

$$f_1'' = \frac{2 z_{11}}{z_{11} + Z_{11}} f_1$$

$$f_2'' = \frac{2 z_{12}}{z_{11} + Z_{11}} f_1$$

$$F_1 = \frac{z_{11} - Z_{11}}{z_{11} + Z_{11}} f_1$$

Thus the presence of the isolated wire has no effect on either the reflected wave or the directly transmitted wave.

Case III. A single wire entering a section consisting of a continuation, and an adjacent grounded wire, Fig. 4d. The transmitted wave $f_2'' = 0$ since the ground wire is at zero potential, and as there are no lumped impedances $U_1 = U_2 = W_1 = W_2 = N_1 = 0$. Then Equations (**50**) and (**51**) give

$$Y_{11}(f_1 - F_1) = y_{11} f_1''$$
$$(f_1 + F_1) = f_1''$$

Solving these two simultaneous equations there are

$$f_1'' = \frac{2 Y_{11}}{y_{11} + Y_{11}} f_1 = \frac{2(z_{11} z_{22} - z_{12}^2)}{(z_{11} z_{22} - z_{12}^2) + z_{22} Z_{11}} f_1$$

$$F_1 = \frac{Y_{11} - y_{11}}{Y_{11} + y_{11}} f_1 = \frac{(z_{11} z_{22} - z_{12}^2) - z_{22} Z_{11}}{(z_{11} z_{22} - z_{12}^2) + z_{22} Z_{11}} f_1$$

If $z_{11} = Z_{11}$, these equations become

$$f_1'' = \frac{2(z_{11} z_{22} - z_{12}^2)}{2(z_{11} z_{22} - z_{12}^2) + z_{12}^2} f_1$$

$$F_1'' = \frac{-z_{12}^2}{2 z_{11} z_{22} - z_{12}^2} f_1$$

so that there is a reduction in the transmitted wave, and a corresponding negative reflection.

Case IV. One of two wires grounded through a resistor, and the other wire left open-circuited, Fig. 4e. There are no transmitted waves, since the wires have terminated. $N_1 = 1/R_1$, $U_1 = U_2 = N_2 = 0$. Then by Equation (**50**)

$$Y_{11}(f_1 - F_1) + Y_{12}(f_2 - F_2) - N_1(f_1 + F_1) = 0$$
$$Y_{21}(f_1 - F_1) + Y_{22}(f_2 - F_2) = 0$$

Solving and substituting impedances for admittances there is

$$F_1 = \frac{R_1 - Z_{11}}{R_1 + Z_{11}} f_1$$

$$F_2 = f_2 - \frac{2 Z_{12}}{R_1 + Z_{11}} f_1$$

If $R_1 = Z_{11}$ then

$$F_1 = 0$$

$$F_2 = f_2 - \frac{Z_{12}}{Z_{11}} f_1$$

so that there is no reflected wave in wire No. 1. Had the incident wave in wire No. 2 been due to induction from wire No. 1 it would have been

$$f_2 = \frac{Z_{12}}{Z_{11}} f_1$$

and in that case the reflected wave F_2 also vanishes.

Appendix II

GENERALIZED THEORY OF IDEAL GROUND WIRES

When a charged cloud approaches a transmission line, charges of opposite sign leak over the insulators and appear on the line and ground wires as bound charges. The density of charge at any point on a particular wire depends upon the electrostatic field gradient due to the superimposed effects of the charge on the cloud and the induced charges on the other wires. It is a simple matter to write the characteristic equations for such a system in static equilibrium, in terms of Maxwell's electrostatic coefficients defined in Appendix I.

Now when the cloud discharges according to some time function $F(t)$, the bound charges on the line wires distributed proportional to a function $f(x)$, are released and form pairs of traveling waves moving away from the region of disturbance in opposite directions. The time of cloud discharge is too short to allow any appreciable readjustment to take place by leakage of a charge of opposite sign over the high resistance of the line insulators. However, this is not the case with the ground wires, which are grounded at the towers through relatively low resistances. The present analysis is restricted to the case of ideal ground wires, that is to wires maintained at zero potential throughout their length by perfect grounding.

Consider an overhead system having m ideal ground wires and $(n - m)$ line wires. Number the ground wires from 1 to m inclusive, and the line wires from

$(m + 1)$ to n inclusive. Let $p_{kr} = p_{rk}$ be the mutual coefficient between the kth and rth conductors. Before cloud discharge all conductors are at zero potential, by virtue of the charges Q_k which have leaked over the insulators. If G is the field gradient due to the cloud alone, and if h_k is the height above ground of the kth conductor, then the field equations during the conditions of static equilibrium before discharge are:

$$\left.\begin{aligned} V_1 &= 0 = G\,h_1 + p_{11}\,Q_1 + \cdots\cdots + p_{1n}\,Q_n \\ V_2 &= 0 = G\,h_2 + p_{21}\,Q_1 + \cdots\cdots + p_{2n}\,Q_n \\ &\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ V_n &= 0 = G\,h_n + p_{n1}\,Q_1 + \cdots\cdots + p_{nn}\,Q_n \end{aligned}\right\} \quad (1)$$

Now suppose that the cloud discharges, so that at any instant t the gradient is given by $G\,.\,F\,(t)$, where $F\,(t)$ is the functional law of cloud discharge, assumed to be uniform over the bound charge distribution $f\,(x)$.

The bound charges on the line wires will be released proportional to the decrease of the gradient, so that the residual charge on the line conductor at any instant (t) is $Q_k\,F\,(t)$. Pairs of traveling potential and current waves are initiated so that for the freely developed waves (see Equation (35), Appendix I)

$$v_k = Z_{k1}\,i_1 + Z_{k2}\,i_2 + \ldots + Z_{kk}\,i_k + \ldots + Z_{kn}\,i_n \quad (2)$$

Now the shapes of traveling waves on all wires depend only on $f\,(x)$ and $F\,(t)$, and are therefore similar. If I_k is the current corresponding to instantaneous cloud discharge, then there exists a function $\phi\,(x, t)$ involving $f\,(x)$ and $F\,(t)$, such that the current wave at any time (t) and point (x) is given by

$$i_k = I_k\,.\,\phi\,(x, t) \quad (3)$$

Similarly, there is a function $\psi\,(x, t)$ associated with the reverse wave. Moreover, by a comparson of Equations (1) and (35) of Appendix I, there must be

$$p_{kk}\,Q_k = Z_{kk}\,I_k \text{ and } p_{kr}\,Q_k = Z_{kr}\,I_k \quad (4)$$

so that (2) may be written

$$v_k = (p_{k1}\,Q_1 + \ldots\ldots + p_{kk}\,Q_k + \ldots\ldots + p_{kn}\,Q_n)\,[\phi\,(x, t) + \psi\,(x, t)] \quad (5)$$

The total potential at x and t therefore is

$$V_k = h_k\,G\,.\,F\,(t) + (p_{k(m+1)}\,Q_{(m+1)} + \ldots\ldots + p_{kn}\,Q_n)\,F(t) + (p_{k1}\,q_1' + \ldots\ldots + p_{mk}\,q_m') + (p_{k1}\,Q_1 + \ldots\ldots + p_{nk}\,Q_n)\,[\phi\,(x, t) + \psi\,(x, t)] \quad (6)$$

The first term on the right is the potential due to the residual field of the cloud; the second term that due to the residual charges on the line conductors; the third term that due to the stationary charges on the ground wires, and the fourth term that due to the traveling waves. There are thus $2\,n$ unknowns: $(Q_1 \ldots Q_n)$, $(q_1' \ldots q_m')$, $(V_{m+1} \ldots V_n)$ and n equations (1) and n equations (6) for their determination. $(Q_1 \ldots Q_n)$ may be found from Equation (1) above. Substituting for the first two terms of (6) its equivalent from (1) there is

$$-V_k + p_{k1}\,q_1' + \ldots + p_{mk}\,q_m' + a\,p_{k1}\,Q_1 + \ldots + a\,p_{km}\,Q_m + b\,p_{k(m+1)}\,Q_m + \ldots + b\,p_{kn}\,Q_n \quad (7)$$

where

$$a = [\phi(x, t) + \psi(x, t) - F\,(t)] \text{ and } b = [\phi(x, t) + \psi(x, t)] \quad (8)$$

The symbolic determinate therefore is:

$$\begin{array}{llll|l} Q_1 \cdots\cdots Q_m & Q_{m+1} \cdots\cdots Q_n & q_1' \cdots\cdots q_m' & V_{m+1} \cdots\cdots V_n & \\ \hline p_{11} \cdots\cdots p_{1m} & p_{1(m+1)} \cdots\cdots p_{n1} & 0 \cdots\cdots 0 & 0 \cdots\cdots 0 & = -G\,h_1 \\ \cdots\cdots & \cdots\cdots & \cdots\cdots & \cdots\cdots & \cdots\cdots \\ p_{1n} \cdots\cdots p_{nm} & p_{n(m+1)} \cdots\cdots p_{nn} & 0 \cdots\cdots 0 & 0 \cdots\cdots 0 & = -G\,h_n \\ a\,p_{11} \cdots\cdots a\,p_{1m} & b\,p_{1(m+1)} \cdots\cdots b\,p_{1n} & p_{11} \cdots\cdots p_{1m} & 0 \cdots\cdots 0 & = 0 \\ \cdots\cdots & \cdots\cdots & \cdots\cdots & \cdots\cdots & \cdots\cdots \\ a\,p_{m1} \cdots\cdots a\,p_{mm} & b\,p_{m(m+)1} \cdots\cdots b\,p_{mm} & p_{m1} \cdots\cdots p_{mm} & 0 \cdots\cdots 0 & = 0 \\ a\,p_{(m+1)1} \cdots\cdots a\,p_{(m+1)m} & b\,p_{(m+1)(m+1)} \cdots\cdots b\,p_{(m+1)m} & p_{(m+1)1} \cdots\cdots p_{(m+1)m} & -1 \cdots\cdots 0 & = 0 \\ \cdots\cdots & \cdots\cdots & \cdots\cdots & \cdots\cdots & \cdots\cdots \\ a\,p_{n1} \cdots\cdots a\,p_{nm} & b\,p_{n(m+1)} \cdots\cdots b\,p_{nm} & p_{n1} \cdots\cdots p_{nm} & 0 \cdots\cdots -1 & = 0 \end{array}$$

(1) Subtract (a) times the (q') columns from the corresponding (Q) columns.
(2) Subtract (b) times the first (n) rows from the corresponding remaining (n) rows.
(3) Add (b) times the (q) columns to the corresponding (Q) columns.

The solution for $V_{(k+m)}$ then takes the form:

$$\left|\begin{array}{lll} p_{11} \cdots\cdots p_{n1} & 0 \cdots\cdots 0 & 0 \cdots - h_1 \cdots 0 \\ \cdots\cdots & \cdots\cdots & \cdots\cdots \\ p_{1n} \cdots\cdots p_{nn} & 0 \cdots\cdots 0 & 0 \cdots - h_n \cdots 0 \\ 0 \cdots\cdots 0 & p_{11} \cdots\cdots p_{1m} & 0 \cdots b\,h_1 \cdots 0 \\ \cdots\cdots & \cdots\cdots & \cdots\cdots \\ 0 \cdots\cdots 0 & p_{m1} \cdots\cdots p_{mn} & 0 \cdots b\,h_m \cdots 0 \\ 0 \cdots\cdots 0 & p_{(m+1)1} \cdot\cdot p_{(m+1)m} & (-1) \cdots b\,h_{(m+1)} \cdots 0 \\ \cdots\cdots & \cdots\cdots & \cdots\cdots \\ 0 \cdots\cdots 0 & p_{(m+k)1} \cdot\cdot p_{(m+k)n} & 0 \cdots b\,h_{(m+k)} \cdots 0 \\ \cdots\cdots & \cdots\cdots & \cdots\cdots \\ 0 \cdots\cdots 0 & p_{n1} \cdots\cdots p_{nm} & 0 \cdots b\;h_n \cdots (-1) \end{array}\right|$$

$$\left|\begin{array}{lr} & 0 \\ & \cdots\cdots \\ \text{Otherwise the same as above.} & 0 \\ & 0 \\ & \cdots\cdots \\ & 0 \\ & 0 \\ & \cdots\cdots \\ & -1 \\ & \cdots\cdots \\ & 0 \end{array}\right|$$

Let R be a matrix consisting of the first $(n + m)$ rows and columns, and the first $(m + n)$ elements of row $(n + m + k)$ in the above determinate.

Let R_r be that determinate of order $(n + m)$ formed by canceling row (r) in matrix R. Then the expansion of the determinate for $V_{(m+k)}$ in terms of its minors takes the form

$$V_{(m+k)} = \frac{G}{R_{(m+n+1)}} (b\, h_{(m+k)}\, R_{(m+n+1)} + b\, h_m\, R_{(m+n)} + \dots$$

$$+ b\, h_1\, R_{(n+1)} - h_n\, R_n - \dots - h_1\, R_1) \qquad (10)$$

but

$$R_1 = R_2 = \dots = R_n = 0 \qquad (11)$$

as may be seen by expanding them in terms of the minors for which the cofactors are the lower right hand elements. Since these elements are in an isolated block, (surrounded by zeros) m elements wide by $(m + 1)$ deep, a point is eventually reached in the expansion, for which the remaining minors contain a solid row of zeros, and therefore vanish.

So Equation (10) finally reduces to the determinate

$$V_{(m+k)} = b\, G \frac{\begin{vmatrix} p_{11} \dots p_{m1} & h_1 \\ \dots\dots & \\ p_{1m} \dots p_{mm} & h_m \\ p_{1(m+k)} \dots p_{m(m+k)} & h_{(m+k)} \end{vmatrix}}{\begin{vmatrix} p_{11} \dots p_{m1} \\ \dots\dots \\ p_{1m} \dots p_{mm} \end{vmatrix}} = b\, G\, D \qquad (12)$$

Thus showing that the potential appearing on any line wire $(m + k)$ is independent of the other line wires, and involves only the heights and potential coefficients of that conductor and the ground wires. The potential is directly proportional to the function.

$$b = \phi\,(x, t) + \psi\,(x, t) \qquad (13)$$

related to the distribution of bound charge $f\,(x)$ and the law of cloud discharge $F\,(t)$.

If there were no ground wires the potential would be (putting $h_1 = \dots = h_m = 0$ in Equation (12))

$$V_{(m+k)}' = b\, G\, h_{(m+k)} \qquad (14)$$

The protective ratio therefore is

$$P\,.\,R = \frac{V_{(m+k)}}{V_{(m+k)}'} = \frac{D}{h_{(m+k)}} \qquad (15)$$

from which specific cases may be computed. This solution is identical to that given by the conventional method of calculation based on the assumption of purely static conditions Thus the protective ratio is independent of the law of cloud discharge, of the initial distribution of bound charge, and of the traveling waves which are formed; and depends only on the geometric configuration of the system, as specified by Maxwell's coefficients and the heights of the conductors above ground.

Appendix III

Periodic Resistance Grounding of Ground Wires

Consider a transmission line consisting of any number of line and ground wires struck at the tower by a lightning bolt. Suppose that the ground wires are grounded at regular intervals through resistances R (due to the tower and its footing). Following the procedure of Fortescue, Atherton, and Cox, in their paper *Theoretical and Field Investigations of Lightning*, (A. I. E. E. Trans., Vol. 48, April 1929, p. 449), the lightning bolt will be represented by a surge impedance Z_o. Moreover, since all of the ground wires are connected together at the tower, they will carry identical potential waves, and therefore a single equivalent ground wire may be substituted as shown by Equations (38) to (42) in Appendix I. However, since the line wires are not constrained to carry equal potential waves, no such equivalent conductor can be substituted for them. In fact, each line wire acts quite independently of the others. Accordingly, then, call the equivalent ground wire, conductor 1 and number the line wires from 2 to n inclusive. The circuit is indicated in Fig. 8. From the point of strike let the towers be numbered 1, 2, 3, etc. Traveling waves arriving at the towers are reflected and refracted, so that there is a great complexity of superimposed waves involved. The problem of their determination is divided into two parts, first, the derivation of the reflection and refraction operators, and second, the development of a scheme for keeping track of the multiplicity of them.

Referring to Equations (50) and (51) of Appendix I and substituting

$U_r = W_r = O,\ N_2 = \dots = N_n = O,\ N_1 = 1/R,\ y_{rs} = Y_{rs}$

there results after some obvious rearrangement, the system of equations

$$\left.\begin{aligned} Y_{11}\,(f_1 - F_1 - f_1'') + \dots + Y_{1n}\,(f_n - F_n - f_n'') &\\ = N_1\,(f_1 + F_1) &\\ Y_{21}(f_1 - F_1 - f_1'') + \dots + Y_{2n}(f_n - F_n - f_n'') = 0 &\\ \dots\dots\dots\dots &\\ Y_{n1}(f_1 - F_1 - f_1'') + \dots + Y_{nn}(f_n - F_n - f_n'') = 0 &\\ f_1 + F_1 = f_1'' &\\ \dots\dots &\\ f_n + F_n = f_n'' & \end{aligned}\right\} \qquad (1)$$

Substituting f_r'' from the last n equations into the first n equations and solving, there is

$$2\,F_r = \frac{M_{1r}}{D}\,N_1\,(f_1 + F_1) = \frac{Z_{r1}}{R}\,(f_1 + F_1) \qquad (2)$$

where M_{1r} is the minor whose cofactor is Y_{1r} in the determinate D formed by the arrangement of Y's in the first n equations of (1). Then by a comparison of Equations (33) and (35) in Appendix I it is evident that $M_{1r}/D = Z_{r1}$. When $(r = 1)$ there is

$$F_1 = \frac{-\,Z_{11}}{2\,R + Z_{11}}\,f_1 = a\,f_1 \qquad (3)$$

and substituting this value back into (2)

$$F_r = \frac{-\,Z_{r1}}{2\,R + Z_{11}}\,f_1 = c\,f_1 \qquad (4)$$

and then from the last n equations of (1)

$$f_1'' = f_1 + F_1 = \frac{2\,R}{2\,R + Z_{11}}\,f_1 = b\,f_1 \qquad (5)$$

$$f_r'' = f_r + F_r = f_r + c f_1 \qquad (6)$$

Equations (3), (4), (5), and (6) specify the behavior of waves at all towers except the one struck. These equations are the same (except for a difference in notation) as those derived by Cox and Slepian, although their solution was restricted to the case of a single ground wire and a single line wire. Notice from these equations that the ground wire and each line wire behave as though the other line wires were not present.

At Tower No. 1, where the bolt is assumed to strike, the initial wave impressed on the ground wire, in terms of the lightning voltage e_o, is

$$f_1 = e_1 = \left(\frac{2 R Z_{11}}{Z_{11} (R + Z_o) + 2 R Z_o} \right) e_o \qquad (7)$$

and the voltage induced on the other wires is

$$f_r = e_r = \left(\frac{Z_{1r}}{Z_{11}} \right) e_1 . \qquad (8)$$

Waves arriving at Tower No. 1 from along the line and ground wires (due to reflections from other towers) are reflected therefrom as

$$F_1 = \left\{ \frac{2 Z_o R - Z_{11} (Z_o + R)}{2 Z_o R + Z_{11} (Z_o + R)} \right\} f_1 = \alpha f_1 \qquad (9)$$

$$F_r = f_r - \left\{ \frac{2 Z_{12} (R + Z_o)}{2 Z_o R + Z_{11} (Z_o + R)} \right\} f_1 = f_r + \beta f_1$$

The potential wave passing from the lightning bolt to the ground wire is e_1. This initial wave will eventually give rise to such a multiplicity of reflections and refractions, that it is hopeless to keep track of them without some graphical or tabular system. The author's first attempts in this direction were with rectangular lattices, which proved unsatisfactory. Mr. S. T. Maunder suggested a diamond shaped lattice which not only avoids interference, but furnishes a uniquely beautiful means for observing the time of arrival of all waves at all junctions, and shows at a glance the direction of propagation of the waves. The schemes shown in Figs. 9 and 10 show the application of this lattice to the ground wire problem. In this case, since all reflection and refraction operators are constants, the waves are reflected and transmitted without change of shape. But the lattice is also applicable, in conjunction with operational calculus, to junctions having inductances and capacitances. Indeed, in studying repeated reflections from terminal apparatus subjected to artificial lightning waves, the author has found these lattices indispensable.

Referring to Fig. 9, the vertexes of the lattice represent the towers, or resistance junctions, and fall at their appropriate intervals. At the left is the time scale measured in the units of time T required for a wave to travel the distance of one span. In this scheme it is evident that waves can only "slide down hill." The lightning bolt strikes at Tower No. 1 causing a voltage e_1, Equation (7), to appear on the ground wires, and a voltage e_r, Equation (8), to appear on the line wires. These waves reach Tower No. 2 where they reflect and refract in accordance with Equations (3), (4), (5), and (6). The transmitted waves pass on to Towers No. 2, 3, etc., at each of which there is a reflection.

In general, at any Tower k and time $m\,T$, (where m is integer), a series of waves are arriving simultaneously from the right and left. For each wave on the ground wire striking a junction (other than Tower No. 1) a fraction a is reflected back towards its origin and a fraction b passes through as a transmitted wave. At Tower No. 1 a fraction α of a returning wave is reflected. On the line wires the situation is slightly more complicated. Equation (4) shows that the reflected wave on the line wire depends only on the incident wave on the ground wire, by a fraction c, and Equation (6) shows that the transmitted wave depends on the incident waves of both the line and ground wire. Therefore the lattice for the line wire cannot be constructed until after that for the ground wire is completed.

Thus these lattices adequately account for the vicissitudes of the numerous waves, and the actual distribution as function of time at any tower, may be found by superimposing the various waves displaced by the time lag of the instants of arrival as shown by the time scale to the left of the lattice. Moreover, the superposition is valid for waves of any shape. If all tower resistances are different the method can still be applied, except that the operators a, b, c would be different at every junction. The equations for the potentials at the first few towers, as obtained from the lattice, are given at the foot of Figs. 9 and 10. In this notation $e_1\,(t - 3\,T)$ means a wave having the same shape as the initial wave $e_1 = e_1\,(t)$, but arriving $3\,T$ later, that is, displaced by that amount on the time axis of superposition.

In Fig. 11 are shown, as function of the tower resistance, the potentials on the ground and line wires, and their difference, for the first three towers. Also there are plotted in this figure the potentials at the first three towers as functions of time for a tower resistance of 100 ohms, and an infinite rectangular initial wave. It is evident that the lower the tower resistance, the greater the reduction in all voltages, and the fewer the number of spans included by the danger zone.

The above results apply to the case of a lightning stroke at the tower. When the direct hit strikes at mid-span the situation is more complicated to analyze, but less severe in effect at the tower. On the assumption that there is more than one ground wire present, but that only one ground wire is hit, the waves at mid-span may be computed by Equations (7), (8), and (9) making $R = \infty$, and using the surge impedance of the single ground wire hit, instead of the "equivalent" ground wire. At the tower a new set of equations similar to Equation (1), must be solved. The lattice is also

somewhat different, since the wave travel between the lightning bolt and the adjacent tower is only $T/2$.

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Discussion

J. E. Clem: There are two points in Mr. Bewley's paper which I would like to bring out. Mr. Bewley discusses the use of a ground wire for preventing direct hits on the line and points out that the spacing from the line wires up to the direct hit wire must be in the order of 35 ft. It has been learned during the past few years from the general study of lightning that the ground wires have given a definite improvement in operating records through the reduction in the number of outages. Evidence obtained during the past year apparently has indicated that a large number of outages from lightning is caused by direct hits. These two facts taken together indicate that the ground wire as ordinarily installed can operate in many cases as a direct hit wire and that it may not be necessary in practise to use as great a separation as indicated.

TABLE I

No. ground wires		Surge impedance $\frac{138.2}{3}x$	Protective ratio: Induced potential	Protective ratio: Traveling wave
0	3 ϕ	$A + 2B$	1	1
	1 ϕ	$3A$		
1	3 ϕ	$A + 2B - \frac{3B_{wg}^2}{A_g}$	$1 - \frac{h_g}{h}\frac{B_{wg}}{A_g}$	$\frac{2}{1 + \frac{Z_0}{Z_n}}$
	1 ϕ	$3\left(A - \frac{B_{wg}^2}{A_g}\right)$	"	"
2	3 ϕ	$A + 2B - \frac{6B_{wg}^2}{(A_g + B_g)}$	$1 - \frac{h_g}{h}\frac{2B_{wg}}{(A_g + B_g)}$	"
	1 ϕ	$3\left(A - \frac{2B_{wg}^2}{(A_g + B_g)}\right)$	"	"
3	3 ϕ	$A + 2B - \frac{9B_{wg}^2}{(A_g + 2B_g)}$	$1 - \frac{h_g}{h}\frac{3B_{wg}}{(A_g + 2B_g)}$	"
	1 ϕ	$3\left(A - \frac{3B_{wg}^2}{A_g - 2B_g}\right)$	"	"
4	3 ϕ	$A + 2B - \frac{12B_{wg}^2}{(A_g + 3B_g)}$	$1 - \frac{h_g}{h}\frac{4B_{wg}}{(A_g + 3B_g)}$	"
	1 ϕ	$3\left(A - \frac{4B_{wg}^2}{A_g + 3B_g}\right)$	"	"

3 ϕ means calculations are made for the three line wires together, which gives the net surge impedance or the average protective ratio.
1 ϕ means calculations are made for one line wire only.

TABLE II

No. ground wires	Surge impedance 3 ϕ	Surge impedance 1 ϕ	Protective ratio induced potential 3 ϕ	Protective ratio induced potential 1 ϕ	Protective ratio traveling wave 3 ϕ	Protective ratio traveling wave 1 ϕ
0	212.7	467.7	1	1	1	1
0–1	193.8	442.4	0.738	0.696	0.954	0.973
0–2	183.7	432.3	0.584	0.540	0.927	0.961
0–3	177.5	427.8	0.474	0.440	0.910	0.956
0–4	174.6	426.0	0.400	0.372	0.902	0.954
1–2*			0.791		0.974	
1–3			0.642		0.956	
1–4			0.542		0.948	
2–3			0.812		0.983	
2–4			0.753		0.975	
3–4			0.844		0.992	

3 ϕ calculations based on 3 line wires net surge impedance average protective ratio.
1 ϕ calculations made on middle wire.
*Indicates passing from section having one ground wire into section having two ground wires. etc.

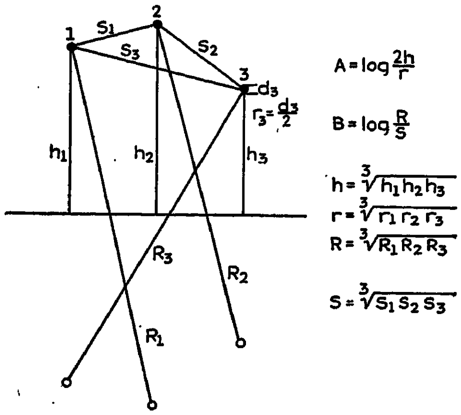

FIG. 1

The practise of increasing the number of ground wires over the section of line adjacent to the station has been extensively advocated during the past few years. The additional ground wires near the station improves the protection on the basis of induced strokes and direct hits. It is surprising, however, what little reduction there will occur in the voltage of a traveling wave when passing into a section of a line having a greater number of ground wires.

I have made calculations for a horizontally spaced line with 1, 2, 3 and 4 ground wires such as illustrated in Figs. 6a, b, c, d. The calculations were made in accordance with the formulas in Table I, and the terms used are defined in Figs. 1, 2, 3, 4 and 5. The derivation of these formulas will be given as an appendix. The results of the calculations are shown in Table II. The calculations were made for three conductors together (3 ϕ) which method gives the average protective ratio, and for a single wire (1 ϕ). For the single wire calculations the center wire was chosen. The protective ratio for induced potentials given in the tabulation is the analytical value and it should be remembered that the protective ratio actually obtained in practise is somewhat better. The protective ratio for a traveling wave is defined as a ratio of the transmitted wave to the incident wave.

In no case is the voltage of a traveling wave reduced more than 10 per cent. But for a case where a line with no ground wires has three or four ground wires added near the station the reduc-

tion is nearly 10 per cent. If, as in the usual case the line already has two wires and two more are added the traveling wave is reduced $2\frac{1}{2}$ per cent and the protection from induced strokes improved 25 per cent. In the laboratory tests to determine the protection of ground wires it was found that the reduction in voltage was considerably more than the calculated value but not

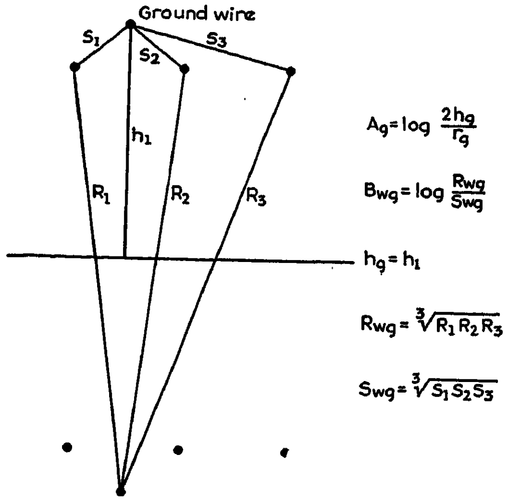

FIG. 2

more than twice as much. If this same condition holds for traveling waves we might expect a reduction of 5 per cent in voltage when passing from a section of line with two ground wires to a section having four ground wires, or of 10 per cent when passing from a section of line having one ground wire to a section having three ground wires. It appears from this that the use

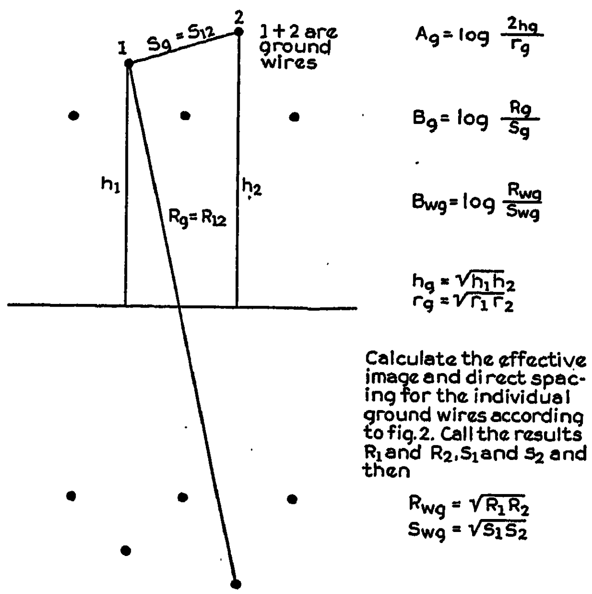

FIG. 3

of additional ground wires adjacent to the station cannot be justified on the basis of the voltage reduction occurring in traveling waves when passing the junction. Further study may, however, indicate that the use of these extra ground wires adjacent to the station is justifiable from the benefits derived through the reduction of direct hits and induced potentials.

APPENDIX

It has been shown elsewhere[1] that the total capacitance to ground in microfarads per mile of three wires in parallel is, approximately

$$C_3 = 3\,C_a = 3\,\frac{0.03883}{A + 2\,B}$$

For definition of A and B see Fig. 1.

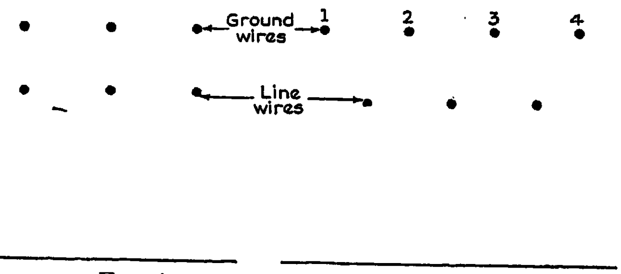

FIG. 4 FIG. 5

Calculate the average image and direct spacing of each ground wire to the line wires according to Fig. 2. Call the results R_1, R_2 etc., S_1, S_2, etc.

$$R_{wg} = \sqrt[3]{R_1\,R_2\,R_3} \qquad R_{wg} = \sqrt[4]{R_1\,R_2\,R_3\,R_4}$$

$$S_{wg} = \sqrt[3]{S_1\,S_2\,S_3} \qquad S_{wg} = \sqrt[4]{S_1\,S_2\,S_3\,S_4}$$

The average spacing of the ground wire to themselves is calculated according to Fig. 1

$$R_g = \sqrt[6]{R_{12}\,R_{13}\,R_{14}\,R_{23}\,R_{24}\,R_{34}}$$

$$S_g = \sqrt[6]{S_{12}\,S_{13}\,S_{14}\,S_{23}\,S_{24}\,S_{34}}$$

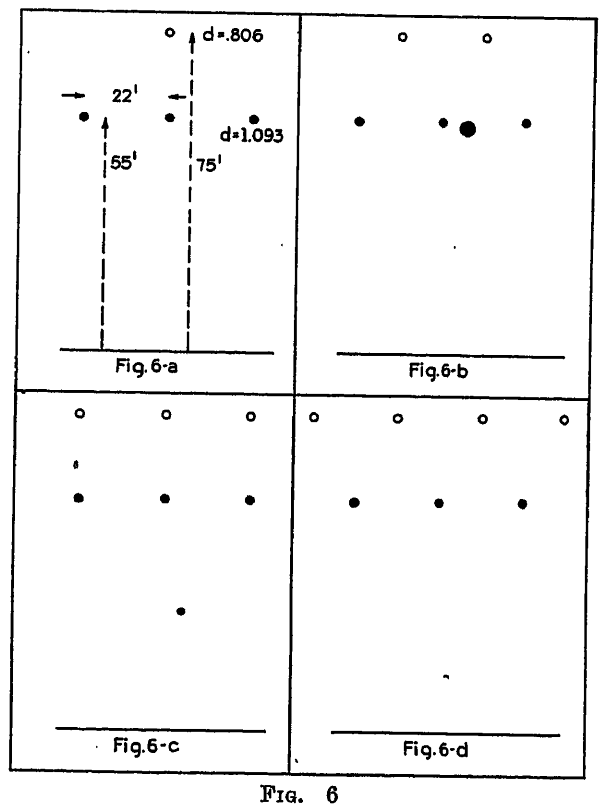

FIG. 6

In the same manner it can be shown that the inductance in millihenrys per mile of three parallel conductors against ground is, approximately

$$L_3 = \frac{0.7411}{3}\,(A + 2\,B)$$

1. *Arcing Grounds*, J. E. Clem, A. I. E. E. TRANS., Vol 49, July, 1930, p. 987.

In this expression the inductance within the conductor material is neglected.

The surge impedance is defined as

$$Z = \sqrt{\frac{L}{C}} = \frac{138.2}{3}(A + 2B)$$

This expression assumes that the so called neutral plane is at a distance h below the conductor and makes no allowance for any voltage drop in the earth itself. This is the conventional method. I expect to submit a paper in the near future showing that there is an appreciable voltage drop occurring in the earth itself. The manner of dealing with additional ground wires is given in the references.[1]

The derivations of the protective ratios for induced strokes has been given previously.[2]

A. O. Austin: Mr. Bewley has given a very fine mathematical treatment of the ground wire theory which at best is very complicated when reflected waves are taken into consideration. The application of the ground wire is becoming more complicated and it is hoped that Mr. Bewley may continue his analysis for other conditions.

By studying the performance of transmission lines, I came to the conclusion some years ago that the ground wire was of very material benefit in reducing potentials on the transmission line in most cases. There were, however, some cases which indicated that the presence of the ground wire was anything but beneficial in dampening out transients. It is not difficult to make comparisons in which it could be shown that the tendency of the ground would be to lower the natural period and also to reduce the attenuation.

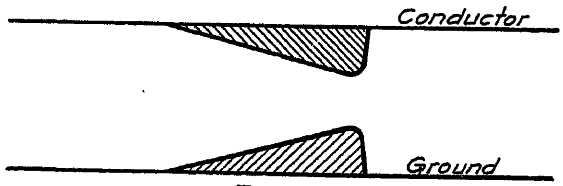

FIG. 7

It is believed that the ground wire should have three functions:

1. Prevent direct hits to the conductor.
2. Increase the effective capacitance of the conductor to ground thereby reducing the magnitude of the potential with the release of a bound charge.
3. Dissipate the energy of the transient in the power conductor.

Mr. Bewley has shown that ground resistance is not as serious as generally believed. The lattice used for studying the ground wire is very ingenious and should be of material benefit in studying a problem which is becoming more complicated with a control of the energy dissipating characteristics of the ground wire.

Referring to Fig. 7, if we assume that the conductor has a traveling wave, a corresponding charge or wave will be induced in the ground. Outside of corona losses, the magnetic field set up by the traveling wave will produce losses in the ground or nearby objects. In addition, the flow of the corresponding charge in the ground will produce $I^2 R$ losses. It is evident that if the resistance in the path of the induced current is zero that the $I^2 R$ losses will be zero. If the conductor had zero resistance as well, the wave could travel on indefinitely without attenuation.

In Fig. 8, a ground wire has been added. The magnitude of the charge on the conductor is reduced over that in Fig. 7 owing to the electrostatic capacitance of the ground wire. The traveling wave or charge induced in the ground is also reduced by an amount equivalent to that taken up by the ground wire.

In general the potential of the bound charge on the ground wire is considerably less than that on the conductor where the induced potential on the ground wire is not sufficient to cause corona, the presence of the ground wire will therefore reduce the potential and corona loss on the power conductor. This results in less attenuation. The ground losses are also less. This is particularly true where the resistance of the ground wire is low and the traveling wave on the conductor positive. If the

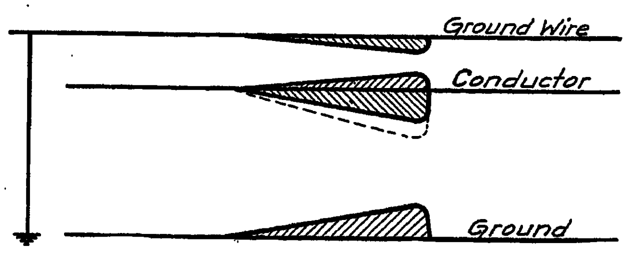

FIG. 8

traveling wave on the conductor is negative and the potential very high or the diameter of the ground wire small and near the power conductor, corona loss may be induced on the ground wire. In this case the ground wire may increase the attenuation. In general, however, it may be said that whether or not a ground wire increases or decreases the attenuation depends upon the magnitude of voltage, the size of the conductor and the polarity. The general effect, however, is to reduce the attenuation which tends to place a higher voltage on the station at a distance than where no ground wire is used.

To obtain the advantage of the ground wire in reducing the potential through an increase in electrostatic absorption, and at the same time using it as a shock absorber or energy dissipator, has led to the sectionalized, or ground wire with controlled impedance, one form of which is shown in Fig. 9. This is the same as Fig. 8 except that the ground wire is sectionalized so that the bound charge opposite that in the power conductor is caused to flow either through the high footing resistance or across an impedance $R S$.

In order to prevent loss in the footing resistance or in resistance which may be placed in the downleads, these resistances may be placed in series with a gap which will not discharge at normal voltage but which will discharge under a transient. Another method of reducing the loss at normal frequency is to shunt the resistance with a reactance which will have but little loss at

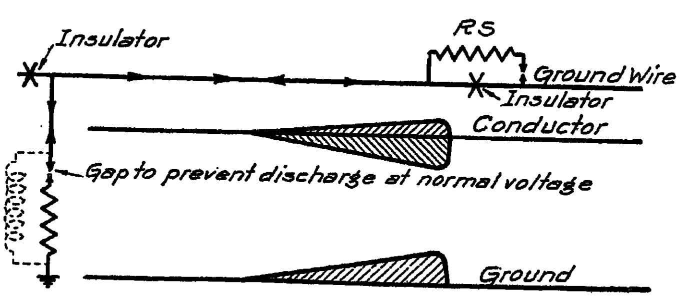

FIG. 9

normal frequency. It is evident that the bound charge upon the ground wire under this condition is made to dissipate energy in the resistances or discharge gaps which may be very material. As the energy dissipated in the ground wire must come from the power conductor, this type of ground wire will dissipate the energy of the traveling wave and greatly increase the attenuation.

Considerable attention has been given to the characteristics of the ground wire so as to make it dissipate the energy of the transient in the conductor and it would seem that this type of

2. *Discussion*, J. E. Clem, A. I. E. E. TRANS., Vol. 49, July 1930, p. 1119.

ground wire may be used to advantage in many installations not only to dissipate the transient in the power conductor but to reduce the magnitude of current in the ground wire which may cause inductive interference under normal operating conditions. While this tends to complicate the study of the ground wire, it would seem that there can be little question as to the efficiency of the method.

A high tower footing resistance is not necessarily a disadvantage, as the traveling wave on the ground wire, due to the release of a bound charge, will tend to raise the potential of the tower

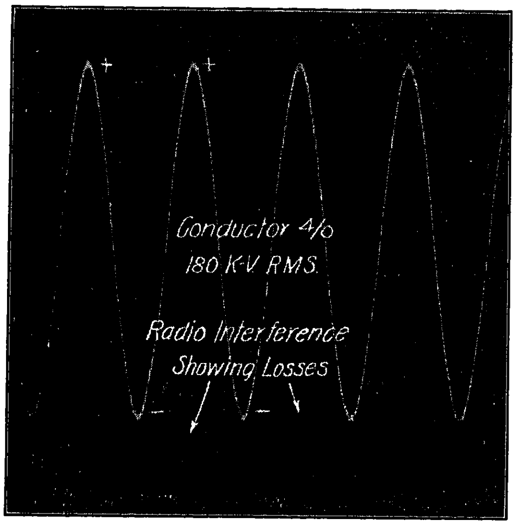

FIG. 10

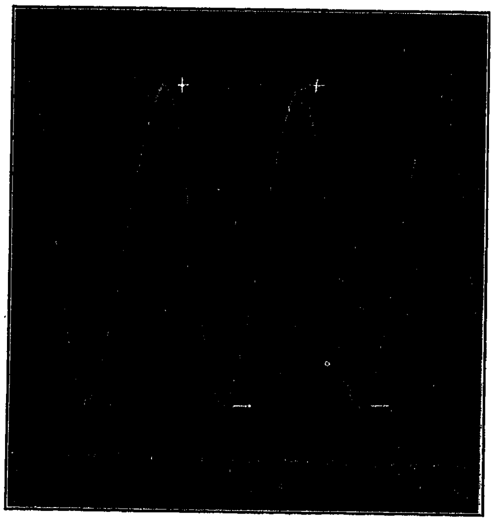

FIG. 11

thereby reducing the potential across the insulator. This, of course, is not true in all cases but tends to offset the disadvantage of a high ground resistance.

It would seem that a high footing resistance might not be detrimental providing the effective capacitance of the conductors to ground is not decreased. It would seem that increasing the effective electrostatic capacity between the conductor and ground is of greater benefit than the reduction in resistance in the tower footing. As the two generally go together, the benefits derived from a high capacitance to ground may be attributed to a low footing resistance.

Fig. 10 supports the theory that the effect of the ground wire in producing attenuation depends upon the magnitude of voltage and polarity. Here it will be noted that the discharge occurs on the positive wave. In Fig. 11 it will be seen that the size of the conductor and potential is such that no discharge takes place. As pointed out, the loss affecting attenuation may take place either on the power conductor or the ground wire. Reflections which materially increase the potential may increase corona losses and attenuation.

To obtain the practical benefits of the ground wire it may be necessary to take into account the effect of ground resistance in raising the potential of the tower as well as the electrostatic absorbing capacitance of the ground wire. In addition it is very important that the size of conductor and ground wire together with the polarity of the transient be given consideration in determining attenuation. It is also necessary to give careful attention to the impedance of the ground wire where the ground wire is sectionalized and absorbing resistances are used.

J. T. Lusignan, Jr.: One of the most thorough contributions to our knowledge of the ground wire theory since Petersen's paper appeared in the *E. T. Z.* of Jan. 1, 1914, is the paper presented by Mr. Bewley. A number of different values for the protection afforded by ground wires against lightning induced voltages, has been given to us by various investigators, some calculated and others measured in the field or laboratory. I am sure that many of us have wondered wherein lay the difference between these values, and which of them could be taken as correct. Mr. Bewley has clearly pointed out the relations between the different methods used, and has shown them to be truly equivalent as far as ideal ground wires are concerned. This then allows us to use with assurance the old conventional method of calculation for static conditions. With a maximum tower footing resistance value of 75 ohms given in Mr. Bewley's paper, the transmission line designer should now be able to pre-determine with fair accuracy the induced voltage protection he can be expected to have under given ground wire arrangements.

With respect to the curves of Fig. 13 some readers might become unduly alarmed at the high voltages reached between conductors and ground wire in midspan for a stroke to the ground wire there. However, I believe that Mr. Bewley merely intends the voltage represented to be that existing at the first instant, as he apparently does not take into account wave travel and reflections. Actually the voltage is considerably reduced after the waves have had a chance to travel to the tower grounds and to be reflected back at opposite polarities. The total time for a 1,000-ft. span would be of the order of a microsecond, and the voltage reduction would of course be greater, the lower the footing resistances.

L. V. Bewley: Both Mr. Clem and Dr. Lusignan have suggested that the 35-ft. elevation of the direct hit wire about the power conductors advocated in the paper is probably higher than necessary except in the case of the most severe lightning stroke. The figure corresponds to a 10,000,000-volt lightning stroke at midspan having a front not exceeding the length of the span, and the impulse flashover characteristic of a needle gap. If the front is longer than the length of the span, there is time for the reflections of opposite polarity from the towers to arrive at midspan and reduce the potential. The amount of this reduction is indicated by the lower curves marked (tower) of Fig. 13 in the paper. The potential difference between the line and ground wires drops from 9,250,000 volts down to 1,500,000 volts at the first reflection, so the danger of side flashing is greatest during the interim preceding the first reflection. Since natural lightning waves having a front of the order of one microsecond have been measured by cathode ray oscillograph stations, it seems reasonable to decide the elevation of the direct hit wire on the basis of the maximum lightning voltage and the one microsecond needle gap spark-over in air, and any lowering of that elevation must be accepted as a departure from 100 per cent protection.

A rational determination of the most *economic* elevation for the direct hit wire must depend upon the probability of occurrence of the most severe strokes. If the great majority of lightning strokes are below 5,000,000 volts and only an occasional one goes up to 10,000,000 volts, then there may be little justification for going to the expense of a high direct hit wire. In any event, to protect a line against a specified lightning voltage four conditions must be met: (1) The direct hit wire must be high enough to prevent side flashes from occurring, based on needle gap characteristics, before the reflections of opposite polarity have arrived. (2) It must be high enough to include the power conductors inside its protective wedge for the lowest clouds. (3) The insulator string must be long enough, based on its own characteristics, so that the potential difference at the tower between line and ground wires is not sufficient to cause a flashover. (4) The clearance of the power conductors at the tower must be great enough, based on needle gap characteristic, to prevent a flashover. These requirements are best met by (a) low line conductors in horizontal plane, (b) short spans, (c) line following the valleys and depressions rather than the ridges; (d) low tower footing resistances. However, these ideals usually conflict with the dollars and cents point of view.

Mr. Clem has given some interesting figures on the effect of introducing extra ground wires, showing that they give very little reduction of an incoming surge. His calculations agree with the statement under the section on *Introduction of Extra Ground Wires* and the simple calculation under *Case III—Appendix I* of the paper. In view of Mr. Clem's contribution I am appending to this discussion the general solution for any number of conductors and any number of ground wires before and after the transition point where the extra ground wires are introduced. My solution does not agree analytically with the expressions given in Mr. Clem's discussion, because no approximations are involved in my general equation. While extra ground wires reduce an incoming surge by only a few per cent, yet that few per cent may prove sufficient so that one or two insulator disks can be removed; thereby conforming to the principle of coordination of system insulation *without changing the factor of safety of the line insulation.* In other words, a line section having extra ground wires and one or two less disks is no more liable to flashover than the fully insulated sections without extra ground wires. This advantage, coupled with the fact that the section next to the station is better protected against both induced and direct strokes may justify the extra ground wires. However, the above argument is worthless if the extra ground wire section is only a few thousand feet long. It must be long enough so that successive reflections will not have a chance to build the voltage up to values that would exist without extra ground wires; and this means that if extra ground wires are used at all that they should extend out from the station for five or six miles. This length also takes care of the requirement mentioned in the paper.

The effect of ground wires on attenuation, discussed by Mr. Austin, has been studied experimentally by McEachron, Hemstreet, and Rudge[3] with artificial traveling waves, and their conclusions seem to fit in fairly well with those of Mr. Austin.

The idea of increasing the dissipative effect of ground wires by including high resistances in the discharge path may operate to increase the attenuation, but delays and decreases the efficiency of the normal function of ground wires as protection against either induced or direct strokes. Mr. Austin's suggestion that a high tower footing resistance is not necessarily a disadvantage is not tenable either from the point of view of the protection of station equipment from induced voltages, or of station and line insulation from direct strokes. Its sole advantage is in reducing the potential across the insulators for induced strokes.

Appendix

Let there be n line wires numbered from 1 to n inclusive. Then Equations (50) and (51) give for the junction where the extra ground wires are introduced

$$\left.\begin{aligned} Y_{11}(f_1 - F_1) + \ldots + Y_{1n}(f_n - F_n) &= y_{11} f_1'' + \ldots + y_{1n} f_n'' \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots & \\ Y_{n1}(f_1 - F_1) + \ldots + Y_{nn}(f_n - F_n) &= y_{n1} f_1'' + \ldots + y_{nn} f_n'' \\ (f_1 + F_1) \qquad\qquad &= \qquad f_1'' \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots & \\ (f_n + F_n) &= \qquad\qquad f_n'' \end{aligned}\right\}$$

Rearranging, there results

$$\left.\begin{aligned} (Y_{11} + y_{11}) f_1'' + \ldots + (Y_{1n} + y_{1n}) f_n'' & \\ = 2 (Y_{11} f_1 + \ldots + Y_{1n} f_n) &= a_1 \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots & \\ (Y_{n1} + y_{n1}) f_1'' + \ldots + (Y_{nn} + y_{nn}) f_n'' & \\ = 2 (Y_{n1} f_1 + \ldots + Y_{nn} f_n) &= a_n \end{aligned}\right\}$$

Hereby the transmitted wave on conductor r is

$$f_r'' = \frac{\begin{vmatrix} (Y_{11} + y_{11}) & \ldots & a_1 & \ldots & (Y_{1n} + y_{1n}) \\ \ldots & & \ldots & & \ldots \\ (Y_{n1} + y_{n1}) & \ldots & a_n & \ldots & (Y_{nn} + y_{nn}) \end{vmatrix}}{\begin{vmatrix} (Y_{11} + y_{11}) & \ldots & (Y_{1r} + y_{1r}) & \ldots & (Y_{1n} + y_{1n}) \\ \ldots & & \ldots & & \ldots \\ (Y_{n1} + y_{n1}) & \ldots & (Y_{nr} + y_{nr}) & \ldots & (Y_{nn} + y_{nn}) \end{vmatrix}}$$

where the Y's are the surge admittances on the incoming side of the junction, and the y's are those on the extra ground wire side of the junction. The ground wires do not enter the equations, except in so far as they change the surge admittances. Hereby the transmitted waves for any combinations of incident waves may be computed.

3. Bibliography 6.

The Influence of Polarity on High-Voltage Discharges

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Member, A. I. E. E. Member, A. I. E. E.

Synopsis.—An experimental investigation of the influence of polarity on high-voltage discharges is reported in this paper. Particular attention is given to those discharges used in high-voltage measurements.

A theory of the formation of Lichtenberg figures is given together with experimental evidence upon which it is based. A polarity indicator utilizing visual Lichtenberg figures is described.

Results of 60-cycle and impulse tests on various types of gaps are given. It is shown that polarity has a distinct effect upon the sparking voltages of all types of gaps. Impulse measurements with grounded sphere-gaps are shown to be subject to serious error unless the polarity effects are taken into consideration.

An explanation of the influence of polarity on spark-over is proposed.

Introduction

HIGH-VOLTAGE discharges in two principal forms are very extensively employed in the measurement of high electrical potentials. For a number of years spark gaps of different types have been in general use and recently extensive use has been made of photographic Lichtenberg figures in high-voltage studies. This paper covers a study of the characteristics of the discharges involved in spark gaps and Lichtenberg figures as affected by electrode polarity.

At the present time the most important use of high-voltage discharges is perhaps in measuring gaps. The spherical-electrode type is the most reliable and is the type generally employed for accurate work. Other varieties such as those employing points and hemispheres are also used. All types of measuring gaps have definite limitations and care must be exercised in their use. Throughout most of the useful range polarity has a very pronounced effect upon the performance of all gaps having dissimilar dielectric flux distribution about the two electrodes. The investigation reported in this paper has to do largely with the influence of polarity on the spark-over voltage of different types of gaps. The ionization phenomena involved in spark-over and in the formation of Lichtenberg figures were also studied.

Lichtenberg figures recorded photographically are valuable in the study of high-voltage transients. The magnitude and character of the voltage wave can be determined with good approximation from the records obtained when certain limitations are recognized. The development of the theory of the formation of Lichtenberg figures proposed in this paper led to the study of other forms of high-voltage discharges and the extension of the theory to explain the observed phenomena.

A Theory of the Formation of Lichtenberg Figures

The Lichtenberg figures in common use for voltage measurements are formed on photographic films or plates by the action of the dielectric flux between a small recording electrode and a plane or large cylinder. The plane or cylinder is insulated with sufficient dielectric material to prevent breakdown at the highest useful voltage which is as a rule approximately thirty kilovolts maximum. The dielectric flux passing from the recording electrode through the air and solid dielectric to the plate electrode is refracted through a large angle at the junction of the air and solid dielectric resulting in a high-voltage gradient on the surface of the solid dielectric, and therefore at the location of the photographic emulsion or recording medium. When the potential difference between electrodes is increased to a certain value, the free electrons in the immediate vicinity of the recording electrode are accelerated to the critical velocity required to produce ionization by collision in the atmosphere under the particular conditions of air density prevailing. These ionization phenomena in the atmosphere surrounding the recording electrode are a normal corona discharge and are easily visible in a darkened klydonograph or surge-voltage recorder. (See discussion of polarity indicator.) The recording of Lichtenberg figures photographically is due to at least two phenomena, the light radiation both visible and invisible resulting from the recombination of the ions associated with the ionization by collision and the electronic bombardment of the silver salts in the photographic film emulsion.

The Negative Figure. The negative Lichtenberg figure is characterized by fine, straight-line striations projecting radially from the recording electrode, (Fig. 1A). This figure is formed by the repelling action of the negatively charged recording electrode on the free electrons in the surrounding dielectric field and on those extracted from the electrode. These electrons are driven radially outward because of the shape of the electric field and bombard the air molecules at the surface of the film as well as the silver salts in the emulsion, producing ionization by collision. Other electrons thus produced also move outward under the influence of the electric field leaving the heavy and relatively immobile positive ions behind. The figure

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increases in size in this manner until the positive-ion space charge reaches a value large enough to reduce the negative field of the electrode below the ionizing potential at the edge of the figure. This condition of equilibrium will be reached quite quickly, resulting in a comparatively small figure, because the free electrons are swept out of the field, reducing the loss of positive ions by re-combination to a relatively small number and because the space position of the positive ions formed is such that a comparatively small space charge will neutralize, at the outer border of the figure, the effect of a large negative electrode potential.

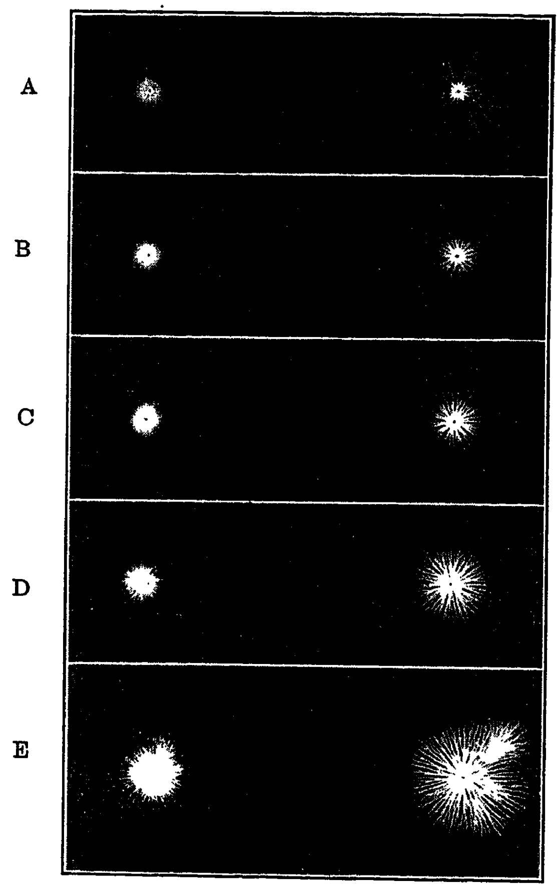


Fig. 1—Lichtenberg Figures

A. 14.5 kv. unidirectional impulse
B. 14.5 kv. quickly forced to 0
C. 14.5 kv. quickly reversed to 7.25 kv.
D. 14.5 kv. quickly reversed to 14.5 kv.
E. 14.5 kv. quickly reversed to 21.8 kv.

When the electrode potential is decreased the mass of electrons forming a negative space charge at the outer border of the figure is released and drawn back toward the electrode by the positive ions, usually forming a very small positive figure superimposed on the original negative. (Fig. 1A.) The higher the rate of removal of potential on the electrode, the more pronounced this effect becomes. (Fig. 1B.)

The Positive Figure. Coarse striations that branch repeatedly at acute angles with the main striation much like the tributaries of a stream characterize the positive Lichtenberg figures, especially those formed by impulse voltages of comparatively short duration. (Fig. 1A.) This figure is formed by the attraction of the free electrons in the field of the positively charged electrode. The electrons move radially inward toward the positive recording electrode bombarding the air molecules at the surface of the film and the silver salts on the photographic surface producing ionization by collision. As the electrons are swept from the field a positive space charge, composed of the relatively immobile positive ions produced by ionization by collision, is left. This space charge is positive and adds its field to the positive field of the recording electrode causing the figure to grow outward. This growth of the figure continues until the positive voltage gradient at the edge of the figure, due to the combined effect of the potential on the electrode and the positive space charge, is less than the ionizing gradient. The positive figure is therefore always larger than the negative figure for a given voltage because the positive space charge subtracts from the field of the negative electrode and adds to the field of the positive electrode.

The branches of the positive striations are probably a secondary phenomena caused by the combined action of the electrode field and the space charge located at the main body of the striation. Electrons located in the space between striations will then have two forces acting on them, one roughly at right angles to the main striation and one radial with respect to the electrode, therefore they will move toward the electrode along the resultant of these two forces. The action of these forces will cause them to flow into the main striation at an acute angle if they start at sufficient distance from the main electrode to allow the previously formed positive space charge to produce sufficient deviation from the radial path.

As in the case of the negative figure, the positive-figure space charge also forms a small figure, of negative polarity, when the electrode potential is suddenly removed, but in a different manner. The positive space charge holds the area surrounding the electrode at a positive potential while the electrode voltage drops below the space value causing the electrode to become negative with respect to the space and hence electrons flow out along the striations superimposing a small negative figure on the positive. (Figs. 1A and B.)

Investigation of Lichtenberg-Figure Space Charges. To definitely establish the existence of a persistent space charge during and immediately after the formation of Lichtenberg figures a circuit was devised for quickly reversing the potential during the formation of the figures. This circuit and the type of wave produced are shown in Fig. 2. It will be observed that by adjusting the water-tube resistances R_1, R_2 and R_3 and sphere-gaps G_1 and G_2 the magnitude of the initial potential and the amount of reversal applied to the klydonograph can be readily controlled. A series

of four Lichtenberg figures taken with this circuit is shown in Fig. 1, parts B to E, inclusive. The voltages used ranged from 14.5 kv. maximum, quickly forced to zero, to 14.5 kv. quickly reversed to 21.8 kv.

In all of the Lichtenberg-figure records the initial negative figure was formed on the left, the initial positive figure on the right and figures of the reverse polarity were superimposed on these. Therefore all of the positive figures on the left are superimposed on negative figures and all of the negative figures on the right are superimposed on positive figures. All of the superimposed figures show a very definite change due to the space charge formed by the original figure. For values of reversed potential up to 50 per cent, the superimposed positive figures are entirely confined to the area ionized by the previous negative figure. For values of reversed potential of 50 per cent and greater the positive ionization breaks over the boundary of the previous negative figure. The negative figures superimposed on the positive grow progressively larger as the reversed potential is increased and follow the ionized paths previously formed by the positive striations. Both the

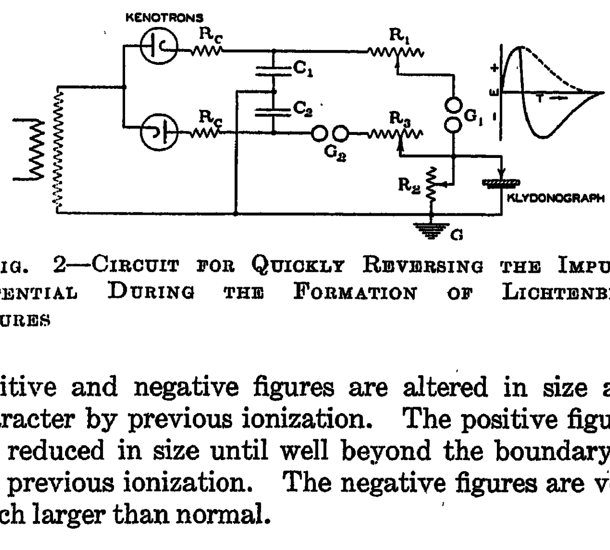


Fig. 2—Circuit for Quickly Reversing the Impulse Potential During the Formation of Lichtenberg Figures

positive and negative figures are altered in size and character by previous ionization. The positive figures are reduced in size until well beyond the boundary of the previous ionization. The negative figures are very much larger than normal.

The Influence of Polarity on Spark-Over Phenomena

Polarity Indicator. The determination of instantaneous polarity in high-voltage circuits has heretofore involved the use of the Duddell type of oscillograph for low-frequency studies and the Dufour cathode-ray oscillograph or the klydonograph for impulse voltage investigations. All of these methods depend upon photographically recording the phenomena. These photographic methods are very accurate and reliable but because of the time and expense involved, limit most investigations to a comparatively few observations. When this investigation of the influence of polarity on high-voltage discharges was started in 1929, it was found that photographic methods for determining the polarity of flashover were so time consuming that it was not practical to continue the study by that method. A very much faster means was needed that would be equally reliable. It seemed reasonable to expect that Lichtenberg figures could be made visible by the use of some florescent screen in the place of the photographic film and some work was done to investigate this possibility. It was found that with a properly constructed instrument the characteristic Lichtenberg figures produced by transients lasting only a few microseconds were easily visible from the ionization of the air surrounding the electrodes without the aid of any florescent material. This instrument is shown in Fig. 3.

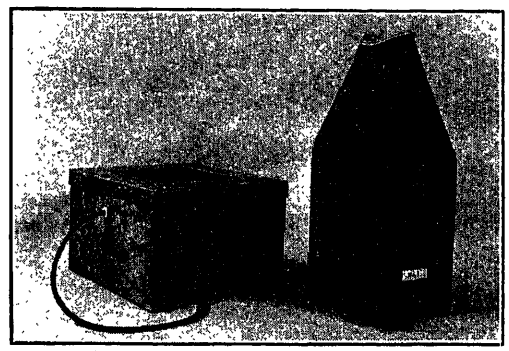


Fig. 3—Polarity Indicator

The polarity indicator consists essentially of two pairs of oppositely connected electrodes enclosed in a light-proof viewing hood. Both the positive and negative Lichtenberg figures are seen simultaneously by the observer and hence the polarity of the discharge is definitely established. The observer is therefore able to make polarity determinations in very rapid succession and a large number of observations can be made in a short time. Each of the curves in this paper was determined from a thousand or more individual spark-aver observations and the time element was of consider-oble importance.

For polarity determinations during 60-cycle tests the instrument was connected as shown in Fig. 4. The

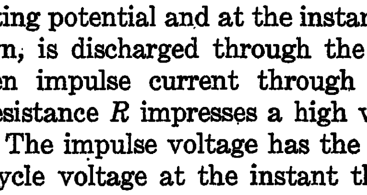


Fig. 4—Circuit for Determining the Polarity of Initial A-C. Spark-Over

capacitance C of the high-voltage circuit is charged by the alternating potential and at the instant the test gap breaks down, is discharged through the resistance R. This sudden impulse current through the polarity-indicator resistance R impresses a high voltage on the indicator. The impulse voltage has the same polarity as the 60-cycle voltage at the instant the gap sparks over and is much larger than the voltage that follows due to the dynamic current.

During the impulse tests the polarity indicator was

connected as shown in Fig. 6. In this case it is not possible to employ a resistance in series with the test gap because the high charging current would produce a voltage drop that would affect the gap spark-over. To avoid this difficulty, the polarity indicator was connected across a portion of the charging resistance R_3. With this connection the instrument has impressed on it an impulse voltage having the same polarity as the generator output. The normal 60-cycle charging current in R_3 does not ordinarily produce a visible

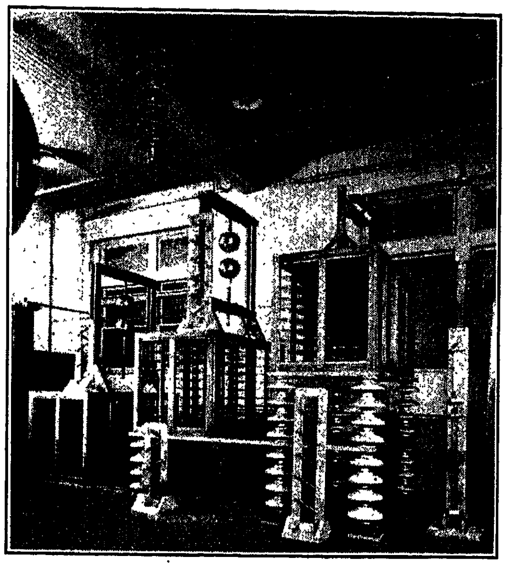


FIG. 5—750,000-VOLT IMPULSE GENERATOR

figure and in all cases it is very much smaller than the impulse figure.

Impulse Generator. The impulse generator used in the tests described in this paper is shown in Fig. 5. The circuit diagram is given in Fig. 6. The three condensers, C_1, C_2, and C_3 are charged in parallel through the graded resistances R_1, R_2, R_3, R_4, and R_5 by means of a high-voltage transformer. At the instant the voltage on C_1 reaches the spark-over value of the 25-centimeter gap G_1, the circuit is effectively closed at that point and C_1 and C_2 are connected in series. The gap G_2, which is set for a slightly higher voltage than G_1, then sparks over and connects C_3 in series with C_1 and C_2. Gap G_3, which is set for a slightly higher voltage than G_2, then sparks over allowing the condensers to discharge through the water-tube resistor R_6. The voltage drop across R_6 is impulsive in character and is applied to the test gap. The charging resistors R_1, R_2, R_3, R_4, and R_5 are of sufficiently high resistance, relative to R_6, to have little effect upon the discharge. If the spacing of the initiating gap G_1 does not exceed approximately 8.5 cm., both positive and negative impulses are obtained. However, as the spacing is increased up to that point when a large total number is taken the ratio of negative to positive impulses, becomes increasingly greater. This follows the characteristic shown in Figs. 12 and 13, *i. e.*, the positive and negative spark-over voltages are not sufficiently different up to approximately 8.5 cm. to cause the 60-cycle spark-overs to be all of one polarity.

In the impulse tests described in this paper the initiating gap G_1 was never spaced greater than 8.5 cm. and hence a number of both positive and negative discharges are obtained from each series of impulses. Furthermore, since the positive and negative spark-over voltages for the 25-cm. initiating gap are essentially the same up to 8.5 cm., the positive and negative impulse voltages are practically identical in magnitude.

Point-to-Plane Gap. The 60-cycle spark-over of the point-to-plane type of gap at all spacings, with the possible exception of very short distances, occurs only when the point is positive with respect to the plane. The spark-over voltage at a given spacing is the lowest of all gaps with the exception of the point to concave-surface types. On continuous voltages at relatively close spacings the negative spark-over voltage is approximately twice the positive and at longer spacings this difference becomes much greater. The continuous-voltage sparking potential of the point-to-plane gap is less when the point is positive and much greater when the point is negative than the d-c. needle-gap spark-over voltage for the same spacing.

Pin-Type Insulators. Tests on high-voltage pin-type insulators of conventional design show that 60-cycle flash-over occurs only on the half of the voltage wave during which the conductor is positive.

This phenomenon is due to the fact that a much higher voltage gradient exists at the conductor than at the pin and intense local ionization at the conductor and tie wire precedes flash-over.

Impulse tests show that pin type insulators flash over at lower voltages when subjected to positive surges on the line than when subjected to negative surges, (Table 1). For the impulse-generator wave used in these tests

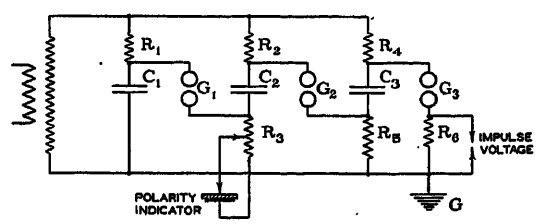


FIG. 6—IMPULSE GENERATOR CIRCUIT

the positive spark-over voltage of a 66-kv. pin-type insulator was 376 kv. maximum and the negative was 427 kv. maximum. The positive impulse ratio was 1.36 and the negative 1.55. This variation is quite large and shows that the insulation strength of transmission lines insulated with pin-type insulators is quite different for impulse voltages of opposite polarities. These tests further show that values of impulse flash-over voltage and impulse ratio, should be defined not only by the voltage wave form used but also by the

polarity of the wave when the voltage gradient is very much higher at one electrode than at the other.

Sphere to Plane. Spark-over tests at 60 cycles were made on a 6.25 cm. sphere-to-plane gap at various spacings up to and including 20 cm. using the polarity indicator.

The tests revealed some very interesting and unexpected spark-over characteristics. These data are given in Table II, and shown graphically in Fig. 7. For sparking distances between 0.5 cm. and 3.0 cm. this gap always sparks over on the half cycle of the voltage wave which makes the sphere negative with respect to the plane and never sparks over when it is positive. For sparking distances between 3.0 and 7.0 cm., the gap may spark over when the sphere is either positive or negative with respect to the plane. In general, near the 3.0-cm. spacing the negative sparkovers predominate. However, the data and curve show a peculiar irregularity in the polarity distribution of spark-over at sparking distances between 4.0 and 5.0 cm. This irregularity when first observed, was thought to be due to chance erratic distribution of spark-overs and it was believed that if sufficient observations were taken, the curve would prove to be a smooth transition from negative to positive spark-overs as the spacing was increased. To check this portion of the spark-over polarity-distribution curve, 1320 individual spark-over observations were made for sparking distances between 4.0 and 6.5 cm. inclusive. This large number of observations checked the original data showing the irregularity in the curve actually exists.

TABLE I
IMPULSE FLASH-OVER DATA FOR PIN TYPE INSULATORS
Standard Mounting

Insulator		Positive				Negative			
Nominal rating kv. r. m. s.	Dry flashover kv. max.	Maximum kv. max.	Minimum kv. max.	Average kv. max.	Impulse ratio	Maximum kv. max.	Minimum kv. max.	Average kv. max.	Impulse ratio
45	202	278	227	253	1.25	354	264	309	1.53
66	276	406	346	376	1.36	435	419	427	1.55

NOTE: Sixty-cycle flash-over on above insulators occurs only when line is positive.
Barometric pressure 755.5 mm.
Temperature, degrees centigrade
Dry bulb 23.2
Wet bulb 16.3

Impulse tests were made on the 6.25 cm. sphere-to-plane gap over the same range of spacings covered by the 60-cycle tests. The data for these tests are given in Table III and are shown graphically by Fig. 8. The impulse tests confirm the 60-cycle tests by showing the spark-over voltage to be lower when the sphere is negative up to approximately 6.25 cm. For spacings greater than 6.25 cm., the positive spark-over occurs at a lower voltage than the negative. It will be noted that for voltages above 155 kv. smooth, average curves have been drawn. However, the experimental points have been checked repeatedly and found to be as indicated. It is therefore probable that the true curve will be found to pass through these points when more completely explored.

Since the impulse generator used gives both positive and negative output waves, depending upon the polarity of the initiating gap at the instant of spark-over, it was necessary to devise a special experimental procedure for determining the impulse data. The impulse generator was adjusted to deliver a definite voltage. The sparking distance of the experimental gap was increased until one impulse in ten of a given polarity failed to spark over. This spacing was termed the minimum gap for that polarity spark-over. The gap was then increased until only one impulse in ten of the chosen polarity caused spark-over. This setting was termed the maximum sparking distance. These two limits represented the spread of the spark-overs at a fixed voltage for the given polarity and their average was taken as the true sparking distance for that voltage and polarity. The mean thus obtained is not the exact

TABLE II
SIXTY-CYCLE SPARK-OVER DATA FOR A 6.25-CENTIMETER SPHERE TO A PLANE

Sparking distance in centimeters	Kilovolts maximum	Per cent of spark-overs	
		Positive	Negative
0.50	12.9	0	100
1.00	24.7	0	100
1.50	35.9	0	100
2.00	43.9	0	100
3.00	64.6	0	100
4.00	75.2	3	97
4.25	77.3	19	81
4.50	79.3	54	46
4.75	81.2	55	45
5.00	83.0	18	82
5.25	84.7	25	75
5.50	86.4	54	46
5.75	87.8	73	27
6.00	89.2	94	6
6.50	91.9	98	2
7.00	95.5	100	0
8.00	99.0	100	0
10.0	106	100	0
15.0	117	100	0
20.0	127	100	0

Barometric pressure 755.6 mm.
Temperature, degrees centigrade
Dry bulb 22.0
Wet bulb 15.5

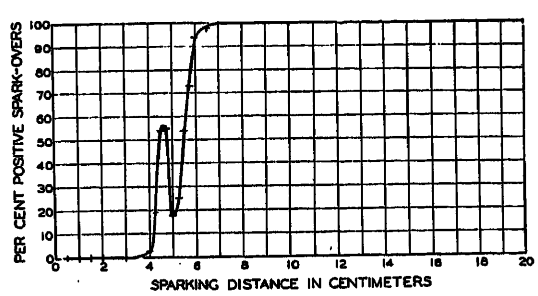


FIG. 7—POLARITY DISTRIBUTION OF 60-CYCLE SPARK-OVERS FOR A 6.25-CENTIMETER SPHERE TO A PLANE

spacing corresponding to the mean voltage, due to the curvature of the spark-over curves, but because of the small differences between maximum and minimum the error is very small. The same procedure was followed for both the positive and negative polarities.

Grounded Sphere-Gaps

2.54-cm. Spheres. Tests were made on a 2.54-cm. sphere-gap over a range of spacings varying from 0.38

TABLE III
IMPULSE SPARK-OVER DATA FOR A 6.25-CENTIMETER SPHERE TO A PLANE

Maximum impulse voltage kilovolts	Sparking distance in centimeters					
	Positive			Negative		
	Maximum	Minimum	Average	Maximum	Minimum	Average
50.9	1.70	1.40	1.55	2.03	1.31	1.67
96.4	4.75	3.00	3.88	4.75	4.60	4.68
110	6.59	4.52	5.56	6.59	5.53	6.06
121	9.14	6.53	7.84	7.00	6.06	6.53
129	11.2	9.10	10.1	7.10	6.44	6.77
155	14.0	12.6	13.3	9.80	8.25	9.03
180	15.8	13.5	14.7	11.0	9.12	10.1
216	19.4	17.8	18.6	14.9	13.0	13.9
241	20.5	19.2	19.9	17.2	14.7	16.0

Barometric pressure 759.4 mm.
Temperature, degrees centigrade
Dry bulb 23.0
Wet bulb 16.0

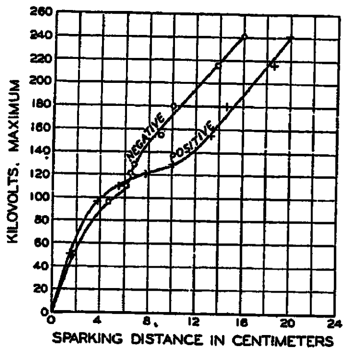


Fig. 8—6.25-Centimeter Sphere-to-Plane Impulse Spark-Over

cm. to 6.35 cm. to determine the spark-over polarity distribution at 60 cycles. The results of these tests are given in Table IV and in Fig. 9. The polarity of spark-over is fairly uniformly divided between the two polarities for sparking distances between 0.38 cm. and 2.0 cm. From 2.2 cm. to 3.2 cm. the spark-overs all occur when the upper sphere is negative. Between 3.2 and 3.8 cm. there is a very rapid transition from all negative to all positive spark-overs. For all spacings investigated above 3.8 cm. the spark-overs were all positive.

6.25-cm. Spheres. Spark-over tests at 60 cycles were made on a 6.25-cm. sphere-gap spaced from 0.5 to 12.5 cm. The data are given in Table V and Fig. 10. Between 0.5 and 1.5 cm., approximately 10 per cent of the spark-overs were positive. There is a very rapid change in the percentages of positive spark-overs between 1.5 and 3 cm. reaching a maximum of 76 per cent positive at 2.25 cm. This characteristic was carefully checked and definitely established as shown. It will be noted that a similar characteristic existed in the case of the 2.54-cm. sphere-gap. This feature does not mean that there is any great difference between the positive and negative spark-over voltages in this region because in order to obtain spark-overs of both polarities the voltages must be practically identical. Between 3.0 and 9.0-cm. spacing no positive spark-overs could be obtained. A rapid transition from 100 per cent negative to 100 per cent positive occurs between 9.0 and 11.0 cm. Above 11.0 cm. all spark-overs obtained were

TABLE IV
SIXTY-CYCLE SPARK-OVER DATA FOR A 2.54-CENTIMETER SPHERE-GAP
Lower Sphere Grounded

Sparking distance in centimeters	Kilovolts maximum	Per cent of spark-overs	
		Positive	Negative
0.381	13.4	32	68
0.635	20.4	30	70
0.952	29.0	10	90
1.27	37.9	58	42
1.59	45.3	56	44
1.91	51.2	39	61
2.22	55.4	0	100
2.54	59.1	0	100
3.18	65.0	0	100
3.49	67.4	60	40
3.81	69.8	100	0
4.45	73.1	100	0
5.08	76.0	100	0
6.35	79.9	100	0

Grounded sphere 20.3 centimeters above ground and fixed in position
Barometric pressure 759.4 mm.
Temperature, degrees centigrade
Dry bulb 22.9
Wet bulb 16.0

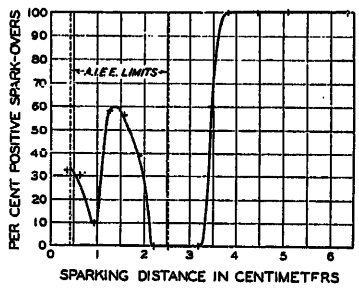


Fig. 9—Polarity Distribution of 60-Cycle Spark-Overs for a 2.54-Centimeter Sphere-Gap

Lower sphere grounded

positive. In portions of the regions where the spark-overs are all of one polarity, or the other, it is probable that a considerable difference exists between the positive and negative spark-over voltages. The impulse tests lend support to this deduction.

Impulse tests on the 6.25-cm. sphere-gap gave the results shown in Table VI and Fig. 11. Up to 1.75-cm. spacing the spark-overs for both polarities occur at practically the same voltages. Between 1.75 and 8.4

cm. spark-over occurs at a lower voltage when the upper sphere is negative than when positive. The percentage difference is maximum at 4.0-cm. spacing at which point the positive voltage is 11.5 per cent greater than the negative. At 8.4 cm. the positive and negative become equal and from this spacing to the upper limit of the tests the positive spark-over voltage becomes rapidly

TABLE V
SIXTY-CYCLE SPARK-OVER DATA FOR A 6.25-CENTIMETER SPHERE-GAP
Lower Sphere Grounded

Sparking distance in centimeters	Kilovolts maximum	Per cent of spark-overs: Positive	Negative
0.50	16.8	16	84
1.00	31.7	8	92
1.50	45.5	8	92
1.75	52.3	32	68
2.00	58.3	52	48
2.25	64.9	76	24
2.35	66.2	40	60
2.50	69.4	12	88
3.00	79.2	0	100
4.00	93.5	0	100
5.00	103	0	100
6.00	111	0	100
6.25	113	0	100
7.00	117	0	100
8.00	123	0	100
9.00	127	0	100
9.50	130	32	68
10.0	132	92	8
11.0	136	100	0
12.0	139	100	0
12.5	141	100	0

Grounded sphere 22.4 centimeters above ground and fixed in position
Barometric pressure 759.9 mm.
Temperature, degrees centigrade
Dry bulb 20.9
Wet bulb 14.2

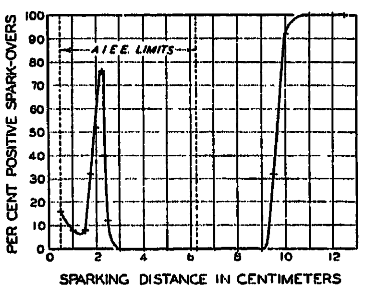


FIG. 10—POLARITY DISTRIBUTION OF 60-CYCLE SPARK-OVERS FOR A 6.25-CENTIMETER SPHERE-GAP

Lower sphere grounded

less than the negative. It is interesting to note that the negative spark-over curve follows the A. I. E. E. standard sphere-gap data throughout the recommended range, (Table VI).

25-cm. Spheres. Table VII and Fig. 12 give the results of 60-cycle tests on a 25-cm. gap. These tests were limited to a maximum spacing of 10 cm. because the upper limit of the available transformer voltage was 235 kv. maximum. Both positive and negative spark-overs, with the negative predominating, were obtained between 1.0 and 8.0-cm. spacing. At 9.0 and 10.0 cm. no positive spark-overs were obtained.

Impulse spark-over data were taken on the 25-cm. gap up to 38.0 cm. spacing. These data are given in Table VIII and in Figs. 13 and 14. It will be noted in Table VIII that as was found in the case of the 6.25-cm. sphere-gap, the average negative spark-over data conforms with the A. I. E. E. standard over the recommended range of sparking distances. The positive curve coincides with the negative up to approximately 5 cm. From this point the percentage difference becomes increasingly higher up to 25 cm., at which spacing it is a maximum and the positive spark-over voltage is 35 per cent greater than the negative.

Due to the construction of the sphere-gap frame it was

TABLE VI
IMPULSE SPARK-OVER DATA FOR A 6.25-CENTIMETER SPHERE-GAP
Lower Sphere Grounded

Maximum impulse voltage kilovolts	Sparking distance in centimeters: Positive: Maximum	Positive: Minimum	Positive: Average	Negative: Maximum	Negative: Minimum	Negative: Average	A.I.E.E. Standard
51.9	1.78	1.70	1.74	1.80	1.65	1.73	1.73
71.6	2.43	2.35	2.39	2.70	2.50	2.60	2.60
100	3.80	3.60	3.70	4.70	4.50	4.60	4.60
113	4.70	4.60	4.65	6.10	5.80	5.95	6.27
129	9.25	5.50	7.38	9.25	7.00	8.13	
146	13.3	10.0	11.7	9.50	7.75	8.63	

Grounded sphere 22.4 centimeters above ground and fixed in position
Barometric pressure 759.4 mm.
Temperature, degrees centigrade
Dry bulb 23.0
Wet bulb 160.

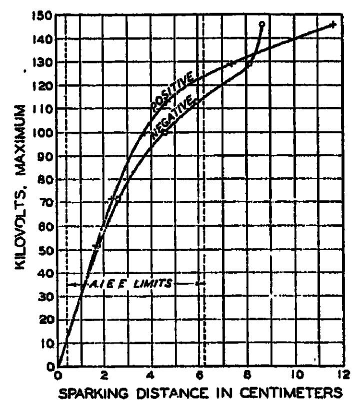


FIG. 11—6.25-CM. SPHERE-GAP IMPULSE SPARK-OVER

Lower sphere grounded

not possible to extend these curves above 40-cm. spacing. However, from the trend of the experimental data at the highest spacings, there is reason to believe that the positive and negative curves cross at some spacing not much greater than 40 cm. This extension would make the complete 25-cm. characteristic curves similar to the 6.25-cm. curves shown in Fig. 11. The positive curve was not carried to the 40-cm. spacing

because the increased voltage would have necessitated operating the impulse-generator initiating gap at spacings in excess of those for which a satisfactory number of positive discharges could be obtained.

The wave form of the impulse voltage impressed upon the test gap probably has a pronounced effect upon the spread of the positive and negative spark-over curves. However, it is believed that the wave form of the impulse generator used in this investigation is quite similar to that of the impulse generators used in other laboratories. Calculation shows that the voltage wave rises to a maximum very abruptly and then decreases to

TABLE VII
SIXTY-CYCLE SPARK-OVER DATA FOR A 25-CENTIMETER SPHERE-GAP
Lower Sphere Grounded

Sparking distance in centimeters	Kilovolts maximum	Per cent of spark-overs	
		Positive	Negative
1.00	30.8	32.0	68.0
2.00	59.3	32.0	68.0
3.00	85.6	12.0	88.0
4.00	110	8.0	92.0
5.00	132	16.0	84.0
6.00	155	16.0	84.0
7.00	176	16.0	84.0
8.00	197	4.0	96.0
9.00	216	0.0	100
10.0	235	0.0	100

Ungrounded sphere 118 centimeters above ground and fixed in position
Barometric pressure 759.4 mm.
Temperature, degrees centigrade
Dry bulb 22.9
Wet bulb 16.0

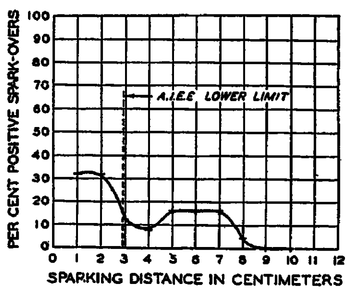


FIG. 12—POLARITY DISTRIBUTION OF 60-CYCLE SPARK-OVERS FOR A 25-CM. SPHERE-GAP

Lower sphere grounded
(Incomplete)

half value in approximately 5 microseconds. The impulse ratio obtained on a 25-cm. needle-gap was 1.78 positive and 1.78 negative and on a 66-kv. pin-type insulator was 1.36 positive and 1.55 negative.

AN EXPLANATION OF THE POLARITY EFFECT IN SPARK-OVER

The dielectric-flux concentration in the point-to-plane gap is many times greater at the point than on the plane. The high-voltage gradient at the point causes local ionization preceding spark-over for all except possibly extremely short sparking distances. When the point is positive, free electrons in the surrounding space are attracted toward the electrode and accelerated to the ionizing velocity in the region where the potential gradient is sufficiently great. These electrons and those liberated by ionization, except those lost by

TABLE VIII
IMPULSE SPARK-OVER DATA FOR A 25-CENTIMETER SPHERE-GAP
Lower Sphere Grounded

Maximum impulse voltage kilovolts	Sparking distance in centimeters						
	Positive			Negative			
	Maximum	Minimum	Average	Maximum	Minimum	Average	A.I.E.E. Standard
127	5.50	4.50	5.00	5.75			4.75
224	8.75	8.25	8.50	9.25	9.25	9.25	9.45
326	13.0	12.0	12.5	16.5	16.5	16.5	16.5
377	15.3	14.3	14.8	24.5	22.0	23.3	22.2
414	19.0	15.5	17.3	32.0	25.0	28.5	
445	21.0	16.8	18.9	37.0	32.0	34.5	
469	22.0	17.0	19.5	40.0	36.0	38.0	
542	30.5	21.5	26.0				

Ungrounded sphere 118 centimeters above ground and fixed in position
Barometric pressure 759.1 mm.
Temperature, degrees centigrade
Dry bulb 21.4
Wet bulb 15.3

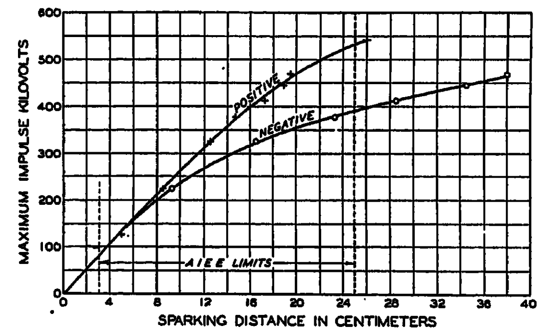


FIG. 13—25-CM. SPHERE-GAP IMPULSE SPARK-OVER

Lower sphere grounded

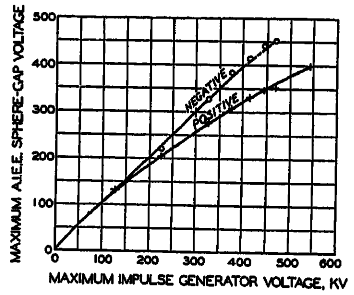


FIG. 14—25-CENTIMETER SPHERE-GAP IMPULSE SPARK-OVER

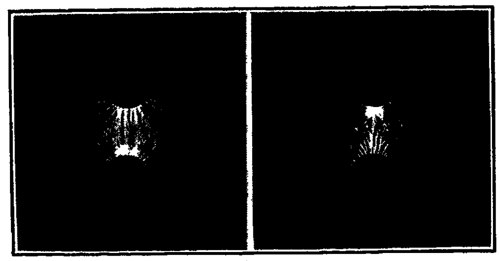
Lower sphere grounded

recombination, are absorbed by the electrode. The relatively immobile positive ions resulting from this ionization form a space charge surrounding the point. This space charge adds to the electrode potential and extends the critical ionizing gradient to a greater distance. In this manner the ionization is progressively

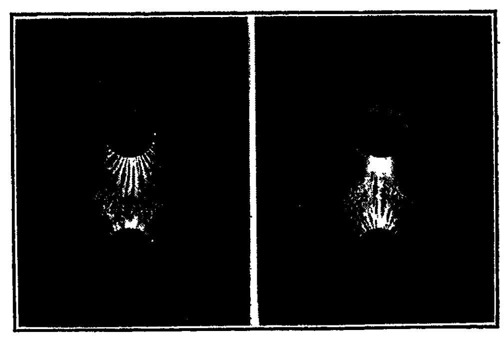
extended outward from the point until the gradient at the outer boundary of the ionized region falls below the critical value or, if the electrode potential is sufficiently high, complete spark-over is established. When the point is negative, free electrons in the surrounding space, together with those extracted from the electrode, are repelled outward at high velocity producing ionization by collision in the region which is above the critical gradient. A positive and a negative space charge are thus formed. The field of the positive space charge opposes the field from the electrode which it surrounds and tends to reduce the resultant flux in the area beyond this space charge. Some of the repelled electrons do not migrate entirely across the gap and are held by the positive space charge at the outer boundary of the ionized region. The decrease in flux reduces the distance to which the ionizing gradient extends from the electrode and hence increases the potential necessary to cause complete spark-over. Positive spark-over therefore occurs at much lower voltages than negative for a given electrode spacing. The above phenomena apply in general to all gaps in which ionization occurs at potentials lower than spark-over and in which this ionization is more intense at one electrode than the other. This condition also obtains in sphere-to-plane gaps and grounded sphere-to-sphere gaps at wide spacings and in practically all forms of high-voltage transmission-line insulation.

When a sphere-gap has a voltage impressed upon it, the positive sphere attracts the free electrons in the surrounding space and when the potential is increased to the proper value accelerates them to the ionizing velocity. The free electrons and those liberated by collision, except the ones lost by recombination, are conducted away by the sphere leaving a relatively immobile positive space charge in the surrounding ionized space. This space charge adds to the positive-sphere potential and extends the critical ionizing potential gradient, as well as the effective radius of the sphere. The negative sphere repels the free electrons in the surrounding space and when the critical voltage gradient is reached produces ionization by collision adjacent to the negative electrode. This action results in the formation of both a positive and a negative space charge. The positive space charge is composed of the relatively immobile positive ions left close to the sphere. Part of the electrons expelled from this region are carried entirely across the gap and the remainder, forming the major part of the negative space charge, are bound near the outer edge of the positive space charge.

At close sparking distances this negative space charge is attracted by the positive sphere and carried away leaving the negative-electrode positive space charge in the combined field of three charges. These charges are the potential on the positive sphere, the positive space charge of the positive sphere and the potential on the negative sphere. This resultant field forces the negative-sphere positive space charge back on the negative electrode producing heavy ionization and extracting large numbers of electrons resulting in local breakdown and removal of the positive space charge in the immediate vicinity (Fig. 15B and D, Fig. 17B and C, Fig. 18). The conducting streamer thus formed extends the negative-sphere potential beyond the positive space charge and the breakdown progresses to the positive sphere. At these close spacings the dielectric flux distribution in the sphere-gap between sparking surfaces is practically unaffected by usual ground proximity. Because of this symmetrical flux distribution on the spheres, spark-over takes place from either the grounded or ungrounded sphere at practically the same



A. 19.8 Kv. B. 19.8 Kv.



C. 28.6 Kv. D. 28.6 Kv.

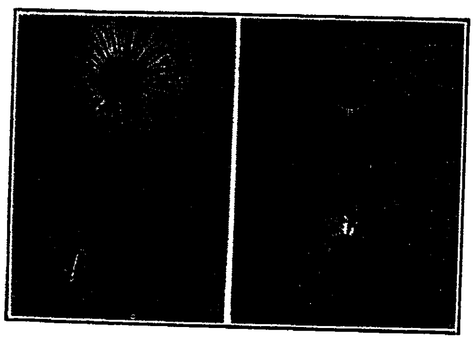
FIG. 15—LICHTENBERG FIGURES OF SPHERE-GAP FIELD SLIGHTLY BELOW SPARK-OVER VOLTAGE, LOWER SPHERE GROUNDED

A. Upper sphere positive, diameter spacing
B. Upper sphere negative, diameter spacing
C. Upper sphere positive, 1½ diameter spacing
D. Upper sphere negative, 1½ diameter spacing

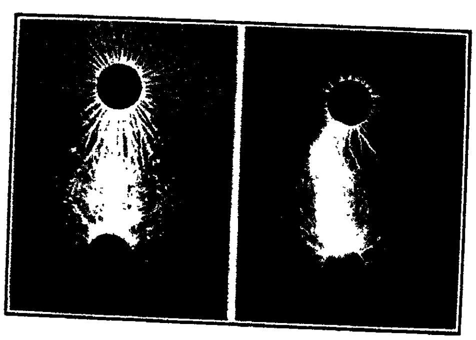
voltage and there is no appreciable polarity effect, Figs. 9, 10, 11, 12, and 13.

For sphere spacings greater than approximately $1.6 \sqrt{R}$ the influence of ground on the flux distribution causes higher voltage gradients to exist on the ungrounded sphere than exist on the grounded sphere at the sparking surfaces. Therefore ionization starts at a lower voltage on the ungrounded sphere. As shown above when the field is symmetrical local breakdown occurs at the surface of the negative sphere at lower voltage than at the surface of the positive sphere when the spacing is sufficiently close for the removal of the negative space charge. When the field becomes unsymmetrical under the influence of ground, local break-

down and spark-over occur at a lower voltage when the sphere having the more intense field is negative. This condition obtains until the spacing is increased to the point at which the negative space charge neutralizes the negative-sphere positive space charge sufficiently to reduce the gradient near the surface of the sphere, when negative, to that value obtaining at an equal positive voltage. At this spacing, which for the gaps and conditions investigated was considerably over diameter separation, the positive and negative spark-over voltages again become equal. For greater spacings spark-over occurs at a lower voltage when the ungrounded sphere is positive as in the case of the point-to-plane gap, Fig. 16.



A. 19.0 Kv. B. 30.0 Kv.



C. 66.5 Kv. chopped at 58.2 Kv. D. 57.6 Kv.

FIG. 16—LICHTENBERG FIGURES OF SPHERE-GAP FIELD

Upper sphere positive,
Lower sphere grounded

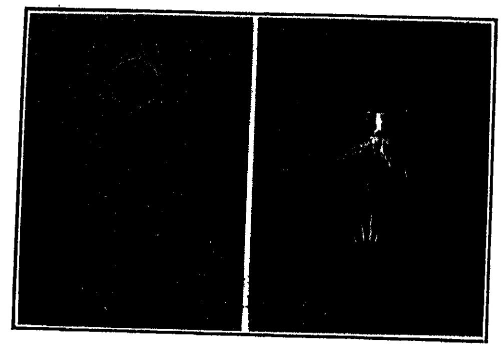
SUMMARY

1. Lichtenberg figures are produced by ionization phenomena at the surface of the recording medium and are visible in a darkened instrument.

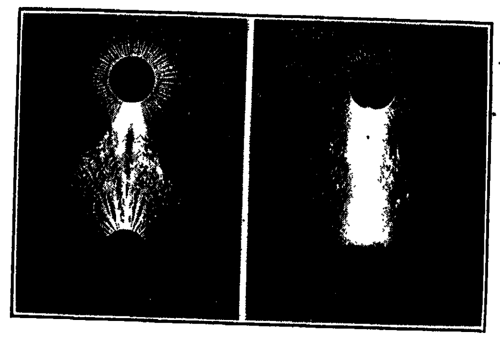
2. The positive figure is extended in size by the positive space charge surrounding the recording electrode. The negative figure is held to a relatively small size by the positive space charge adjacent to the electrode. The existence of these space charges is clearly demonstrated when figures of opposite polarity are quickly superimposed.

3. Tests with different types of gaps show that polarity has a pronounced effect upon spark-over.

4. The point-to-plane gap at a given spacing sparks over at a much lower voltage when point is positive than when negative, except for possibly very small spacings.



A. 19.5 Kv. B. 43.5 Kv.



C. 66.5 Kv. chopped at 58.2 Kv. D. 62.9 Kv.

FIG. 17—LICHTENBERG FIGURES OF SPHERE-GAP FIELD

Upper sphere negative,
Lower sphere grounded

FIG. 18—IMPULSE SPARK-OVER ON 25-CM. SPHERE-GAP AT DIAMETER SPACING

Upper sphere negative
Lower sphere grounded

This characteristic is typical of all gaps having dissimilar electrode gradients when local breakdown precedes spark-over, and is due to the space charge extending the

field of the higher-gradient electrode when positive and suppressing the field when negative.

5. Pin-type insulators spark over at lower voltage when line is positive than when negative, due to local breakdown occurring first on the line. The impulse ratio is lower positive than negative.

6. The grounded sphere-gap sparks over at the same voltage with ungrounded sphere positive or negative up to spacings of approximately 1.6 $\sqrt{R}$.

7. For the conditions investigated the grounded sphere-gap sparks over at a lower voltage negative than positive at spacings ranging between approximately 1.6 $\sqrt{R}$ and well over diameter separation. This characteristic is due to high local negative gradients caused by the negative-electrode positive space charge.

8. At wide spacings the grounded sphere-gap sparks over at lower voltages positive than negative, (4).

9. Near diameter spacing the grounded sphere-gaps investigated spark over at much lower impulse voltages negative than positive. The shape and duration of the impulse wave probably have a pronounced effect upon this difference.

ACKNOWLEDGMENT

The published works of other investigators have been drawn upon freely in the preparation of this paper and a partial list is given in the bibliography.

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Discussion

Geo. S. Smith: In 1928 Mr. E. J. Wade and I observed a decided polarity effect on certain types of insulators, while determining the arc-over time lag under impulse conditions. The greater portion of our data was obtained by means of the Dufour oscillograph. The impulse generator used gave negative polarity on the high-voltage side while the grounded side was positive.

When using slowly rising wave fronts approaching the time required for a quarter wave length of a 60-cycle wave, voltages averaging 50 per cent greater than the 60-cycle value were required to produce an arc over the insulator. With the insulator inverted and the negative applied to the pin, or with the polarity reversed on the upright insulator, the arc-over voltage was reduced to an average of about 8 per cent above the standard 60-cycle value.

A check on these impulse values was obtained by using direct current and steadily raising the voltage until arcover occurred. The values thus obtained checked the results of the impulse tests very closely.

Arc-over tests were also made using 60-cycle voltage and taking oscillograms on a Dudell type oscillograph of the break-in voltage. The oscillograms showed every arc to occur on the same half of the wave, that is when the cap or line side of the insulator was positive.

It is interesting to note, in the set of curves shown, that for the 15-kv. pin type insulator tested, the difference between the positive and negative arc-over values decreases as the steepness of the impulse wave front is increased. They both approach

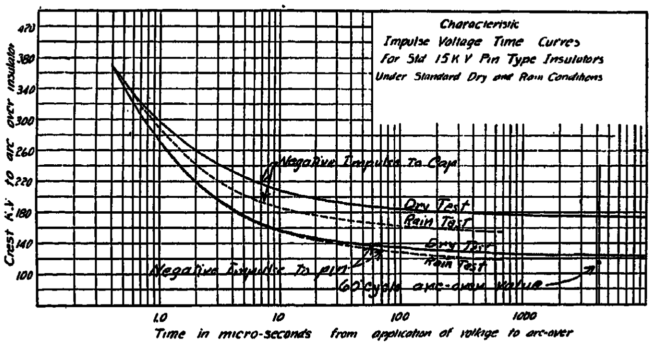

FIG. 1

the same limiting value at very steep wave fronts. Similar tests under standard rain conditions also approached this same limiting value as the curves indicate.

Tests made on suspension type insulators showed little or no effect of polarity on the arc-over values.

While some small differences in results were observed with the pin type insulator inverted as compared with the same polarities applied when erect, the differences were so small, it might be safely concluded that the insulator mounted on a pole as in use is affected very little by the earth beneath. Thus the polarity effect is almost entirely caused by the distribution of the electrostatic lines of flux between the cap or line and tie wires, and the pin with its support.

H. L. Rorden: As far as is known at present, the effect of polarity on spark-overs is not susceptible to a mathematical treatment. It would seem therefore, that voltage differences due to polarity may be attributed to inherent physical properties, the nature of which must be determined empirically. This was recognized by Carroll and Lusignan[1] and later Dr. Lusignan demonstrated spark-over differences due to polarity at power frequencies.[2]

A factor of major importance in the investigation of the effect of polarity on spark-overs is the lack of an accurate voltage measuring device for high potentials. The crest voltmeter

1. *The Space Charge that Surrounds a Conductor in Corona*, by J. S. Carroll and J. T. Lusignan, A. I. E. E. Trans., January 1928, p. 50.

2. *A Study of High-Voltage Flashovers*, by J. T. Lusignan, A. I. E. E. Trans., January 1929, p. 246.

probably used most extensively for this purpose,—the sphere-gap,—has proven itself to be only approximately correct. In the extensive investigations of high-voltage phenomena carried on under the direction of F. W. Peek, Jr. surprising disclosures have resulted from comparing impulse spark-over voltages of various electrodes with both polarities. In these investigations, the cathode-ray oscillograph has been unique in obtaining comparative data, in disclosing the approximate variations to be expected in sphere gap measurements, and in the spark-over of other electrodes. If oscillograms could but be used for an accurate voltage calibration, the story would be complete. Oscillograms do, however, give us comparative information.

It has long been known that sphere-gaps, particularly at relatively higher spacings, are not free of time lags. But since in general, sphere-gap calibration curves must depend on voltages at power frequencies, the effect of polarity on their sparkover introduces an error that cannot be so easily detected, and is much more difficult to correct. With the cathode ray oscillograph, and a lightning generator with its polarity controlled, it is found that sphere-gaps generally require a higher voltage with a positive wave to spark over a given spacing, the difference ranging up to 12 per cent, depending on the wave form and the per cent overvoltage held. In agreement with the results

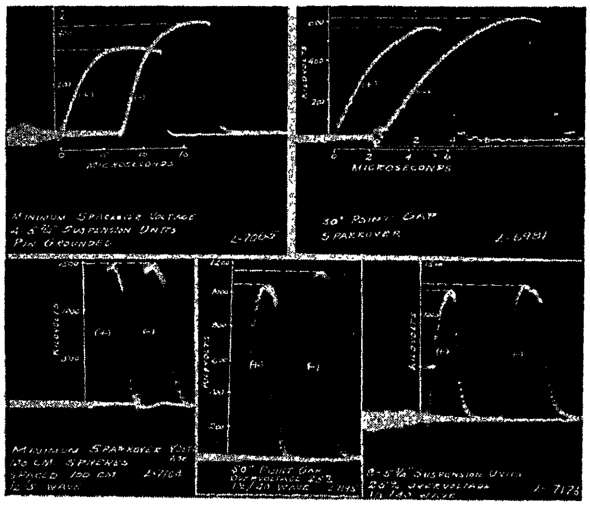

FIG. 2—SPARK-OVERS OF VARIOUS ELECTRODES WITH BOTH POLARITIES

obtained by Messrs. McMillan and Starr, is the fact that only at relatively small spacings do the negative polarity spark-overs equal or exceed the voltage of the positive wave, for spheres ranging from 25 to 100 cm. in diameter. However, the larger spheres show less difference at relatively large spacings than do the smaller ones, there being a maximum of 4 per cent difference found in 100 cm. spheres at diameter spacing, for various wave forms.

With non-uniform electrodes the negative polarity wave usually has the higher spark-over value, although it is frequently (but not always) found that a higher energy input to the lightning generator is necessary with positive polarity waves. This higher negative spark-over has been found to run as high as 22 per cent for insulator strings, and may be very much greater for a point-to-plane spark-over. However, merely inverting a string of suspension units may reverse the order of the polarity requiring the higher spark-over voltage. Point gap spark-overs are found to require a higher voltage for the negative wave consistently, with various wave forms, and within the range of 30 to 130 cm. spacing.

The accompanying oscillograms illustrate spark-over differences due to polarity, for the various electrodes and with the various wave forms as shown. Voltage scales are given where oscillographic deflections could be favorably compared with differences found by sphere gap measurements. In the many instances where fair agreement could not be obtained, it was assumed that an appreciable difference existed in the sphere-gap spark-overs.

In the paper presented by Messrs. McMillan and Starr, no direct indication is given of the method used for measuring the impulse voltage. And since it is a measurement of voltage that determines what differences exist due to polarity, this would seem to be an item of major importance. Obviously, the transformer ratio cannot give dependable results, since, as is pointed out, the space charge preceding spark-over is of a different nature for the two polarities, and therefore the energy drain, with its consequent loss of voltage is not constant. Tests and oscillograms show, that particularly with a series-multiple type of generator, this factor assumes huge proportions. Since the sphere gap itself is shown to be in error, we might infer that the Lichtenberg figures are employed as a crest voltmeter. But since they also are susceptible to considerable variation, values thus obtained might involve an appreciable error.

The plotted results of Table VIII, given in Fig. 13, show an increase in spark-over voltage for 25-cm. spheres of the positive over the negative, of 35 per cent at diameter spacing. Such an extreme difference seems incredible, and is not in agreement with oscillographic records. Since these curves depend upon an accurate measurement of voltage, it would be very desirable to know how these voltage measurements were obtained.

F. O. McMillan and E. C. Starr: It is interesting to observe that the small amount of data taken on pin type insulators in this investigation is in agreement with the results obtained in the extensive investigation conducted by Messrs. Wade and Smith. Their work made use of the cathode-ray oscillograph for determining the polarity effects. Mr. Smith summarizes their results in his discussion and they are given in more detail in an article published in the *Electrical World* for August 18, 1928. (See bibliography.)

Mr. Rorden in his discussion states that it would be very desirable to know how the voltages were measured during the investigation. The voltages were measured by the use of sphere gaps using special precautions, as explained below, to avoid the limitations they were found to have, due to polarity effects. It was recognized from the beginning of the investigation that precision methods for measuring high voltages are not available. Even the Dufour type of cathode-ray oscillograph usually depends on sphere-gap measurements and the determination of the ratio of a high-ratio potentiometer for its calibration. Furthermore, the cathode-ray oscillograph when used only for comparative purposes in the determination of polarity effects is not free from polarity errors unless the voltage dividing potentiometer and all of its circuits are free of corona during the measurement.

In the event corona is present on the high-voltage elements of the potentiometer the voltage ratio positive is different from the negative ratio because of the widely differing extents of corona for the two polarities. This difference is dependent on the character and spacing of the electrodes.

The impulse generator used in the investigation reported in the paper was carefully calibrated by means of sphere-gaps. It was observed that a marked correlation existed between the impulsive negative output voltage as indicated by sphere-gap measurement and the maximum 60-cycle voltage of the initiating gap. These data are shown in the accompanying table. It will be noted that the "output factor" which is the ratio of the average negative impulse voltage to the maximum 60-cycle spark-over voltage of the initiating gap is practically constant and equal to 2.62 for all output voltages up to the highest value measurable with the available sphere-gap. The 60-cycle data show that the 25-cm. sphere-gap sparks over on both polarities only up to a sparking distance of 8.5 cm. Beyond this spacing and within the recommended range all spark-overs occur on the negative

half cycle. Therefore, it is evident that sphere-gap calibration data apply to the negative voltage and not to the positive throughout the entire range. Therefore, the negative impulse voltages were used for computing the output factor.

Since the initiating gap spacing never exceeded 8.5 cm. the positive and negative tripping potentials were the same and the stored energies were identical for both polarities. The impulse generator is very compact and practically free from stray discharges which insures the delivered energies and maximum potentials being the same for both polarities. To verify these conditions the spark-over voltages, positive and negative were measured for a well isolated 35-cm. point gap 5.25 times its spacing from any grounded object. As determined by output ratio, the average spark-over voltages, positive and negative, as determined from 100 observations, checked within one per cent. A 25-cm. sphere-gap connected in parallel with the point gap and so spaced that it arced over on approximately 10 per cent of the impulses had no influence on the parallel point-gap spark-over either positive or negative, except when it sparked completely over. These data are significant because they show that the impulse generator was delivering the same maximum voltage positive and negative, and furthermore, the positive and negative wave shapes were essentially the same because the point-gap spark-over voltage depends not only on maximum voltage but also on wave shape. From the results obtained above it appears that the energy drain due to discharges preceding complete spark-over have no more effect on one polarity than the other in the particular lightning generator used.

The phenomenon of polarity effect in sphere-gap spark-over is dependent wholly on the flux distribution on the spheres. Therefore, gaps operating under different conditions such as in the vertical or horizontal position, in the proximity of high-voltage conductors or ground will exhibit different polarity characteristics because of the difference in extraneous fields. Observation has been made of a sphere gap which had practically inverted polarity characteristics because of the proximity of high-voltage conductors and its unusually great distance above ground. It is possible in the case of the 100-cm. sphere-gap test reported by Mr. Rorden that extraneous fields were influencing the polarity effect.

VOLTAGE CALIBRATION OF IMPULSE GENERATOR

Impulse generator initiating gap		Impulse generator output voltage 25-cm. sphere-gap		Impulse generator output factor
Sparking distance centimeters A	60-cycle spark-over voltage kv. maximum B	Average sparking distance cm. negative impulses (Table VIII) C	60-cycle spark-over voltage kv. maximum D	$\frac{D}{B}$
3.00	85.6	9.25	221	2.58
4.63	125.	16.5	327	2.61
5.50	144.	23.3	385	2.67
6.16	158.	28.5	415	2.63
6.68	170	34.5	443	2.61
			Average	2.62

NOTE: The first three values given in column D were taken from the A. I. E. E. sphere-gap spark-over voltage data. The last two values were taken from an empirical spark-over curve.

Corona Loss Measurements on a 220-Kv. 60-Cycle Three-Phase Experimental Line

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Synopsis.—*Corona loss measurements were made on seven different conductor specimens. The losses were measured directly, on a three-phase line 700 ft. long, by means of three single-phase high-voltage wattmeters. The object of the test was to obtain data for the choice of conductor to be used on a 220-kv. 60-cycle line. The results show the effect of weathering of conductors, the comparison of conductors of two different diameters, the effect of size of strands and the method of stranding and also the effect on new conductors of the change in surface conditions caused by rain and washing.*

* * * * *

Introduction

The purpose of these corona loss measurements, made at the Ryan Laboratory, Stanford University, was primarily the comparison of different conductors for use on a 220-kv. transmission line. Among the things that were to be studied was the effect on corona loss of the different methods of stranding, size of strands, the spacing and configuration of conductors, the difference between a conductor 0.91 in.

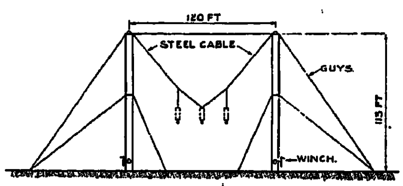

FIG. 1—TRANSVERSE SECTION OF TEST LINE

in diameter and one 1.0 in. in diameter and also the difference, if any, between copper and aluminum conductors.

In order to closely simulate actual operating conditions the tests were to be made on a three-phase line.

Description of Equipment

The test line was 700 ft. long and the conductors were supported between steel masts as shown in Fig. 1 and Fig. 2. With this arrangement the conductors to be tested were laid out on the ground, fastened onto the insulator strings and raised into position by means of winches, one on each mast.

The dimensions involved in fastening the insulator strings on the steel cable were determined mathematically and checked by means of a model.

There were several reasons for starting the test specimen 350 ft. away from the laboratory and continuing it on for two spans of 350 ft. each. The dead ends at the building could be made up once for all and did not have to be lowered for changes in elevation of the line or spacing of the conductors, nor even for a change in configuration from the horizontal to the vertical. Another advantage was that the test line was well in the clear of the building thus eliminating any possibility of stray electric fields in that direction.

The shielded leads from the building to the test specimen were hollow concentric-lay aluminum conductors 1.1 in. in diameter. At the time this cable was made, two No. 12 rubber covered copper wires were placed on the inside of the cable. These two wires were used as the lead from the wattmeter to the test specimen.

The line was energized by means of three 350-kv.-350-kv-a. transformers which were connected delta on the low-voltage side and Y on the high-voltage side with the neutral grounded. The source of power for these transformers was a 1500-kv-a. 60-cycle sine wave motor-generator set. The voltage was controlled by means of a rheostat in the exciter field. The root-mean-square value of the line voltage to ground was obtained by means of the voltmeter coil in the transformers. With the line connected, the reading of the voltmeter across this coil was checked against the voltage from line to ground as measured with a sphere gap. The agreement was within one per cent which is about the limit of accuracy for the sphere gap.

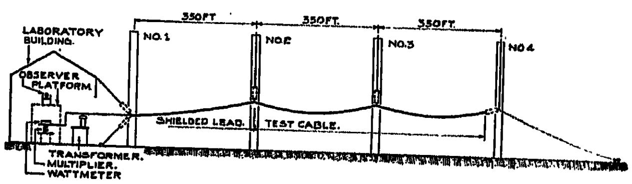

FIG. 2—LONGITUDINAL SECTION OF TEST LINE

Measurements with a harmonic analyzer showed that the third harmonic was the greatest and this was less than one per cent at 260 kv.

The corona loss at 60 cycles was measured directly by means of three high-voltage wattmeters, one connected in on each conductor. The diagram of connections of one of the wattmeters is shown in Fig. 3. Each wattmeter assembly was almost identical with that described in a former paper.[5]

On account of using a sine wave generator and due to

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5. For references see bibliography.

the reliability of the voltmeter coils in the transformers, the ohmmeter and crest voltmeter described in the paper just referred to were omitted in this set-up. The milliammeter that measured the current through the water resistor wattmeter multiplier was connected in the ground side of the resistor. A three-cylinder piston pump supplied water to all three resistors. The use of salt water for changing the resistance of the multiplier was the same as in the former set-up. The shielding cages containing the wattmeter instruments were mounted directly on top of the upper shields of the water resistors. The meters were read by means of telescopes from platforms directly above.

In all of these tests, temperatures and relative humidities were determined outside near the line, readings being taken immediately before and after each test. The wet and dry bulb thermometers were placed in front of a fan for consistent results.

Shielding Tests

At the beginning of the tests it was necessary to make certain balances and adjustments of the shielding

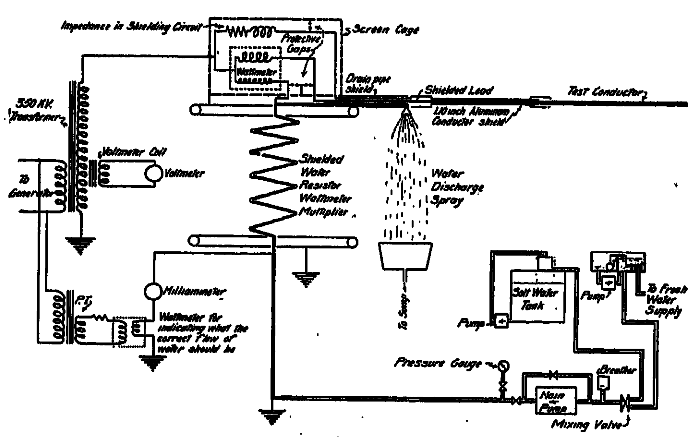

Fig. 3—Wattmeter Connections

circuits. From previous tests, most important of which was the double conductivity test, and also with further check on the present set-up it was found that the water resistor multiplier was, for all practical purposes, correctly shielded.

The shielded lead from the wattmeter to the test conductor was 440 ft. long. The capacitance between this lead and its shield was 0.04 microfarad. This capacitance shunts the field or current coil of the wattmeter and due to the low power factor of these measurements the current through this capacitance would shift the phase angle of the current through the field coil of the wattmeter and cause serious error. This capacitance cannot be eliminated; however, if the potential of the shield is made the same as that of the lead there can be no flow of current through the capacitance. This was accomplished by inserting an impedance in the shielding circuit as shown in the diagram of Fig. 3. The constants of the impedance in the shielding circuit were obtained as follows: The charging current to the test specimen was measured as was also the charging current to the shielding circuit. The inverse ratio of these currents gives the ratio of the impedances in these two circuits. The resistance and inductance of the current coil of the wattmeter are given by the maker. With the above information, coils were designed and made up for the three shielding circuits. One very good check of the proper shielding of the circuits was made by using a wattmeter of a different range and impedance in each of the three phases. Three tests were made and for each test each of the three wattmeters was in a different phase. Therefore, for each phase three sets of readings were obtained each with a different wattmeter. Each change of wattmeters involved a change in the shielding impedances. After slight errors in the shielding had been located and eliminated the measured loss was the same irrespective of the wattmeter arrangement.

Observations were made on the line at night. The voltage at which corona was first seen and also heard on the conductor agreed with the voltage at which the wattmeters began to show a power loss from the line. Corona brushes were observed on some of the insulator units next to the conductor. Proper shielding of the insulator strings eliminated these brushes. Since the losses on one suspension and one dead end string were included with the losses of each conductor it was necessary to determine the magnitude of such insulator losses. The losses were measured on each of the suspension strings that support the conductors at the point where the shielded lead connects to the test specimen. The losses were found to be as follows at a voltage between lines of 295 kv. with 13 units in each string:

Relative humidity	Loss on string No. 1	No. 2	No. 3
45%	3.5 watts	5.0 watts	5.0 watts
76%	60.0 watts	78.0 watts	101.0 watts
81%	132.0 watts	124.0 watts	172.0 watts

From the values in the above table it is obvious that insulator losses can be neglected for fair weather conditions such as existed when the corona loss curves given in this paper were taken. Corona loss data not shown in this paper were taken at the higher humidities, but on account of insulator loss it is difficult to say just how much the loss was increased by the higher humidities. One thing was definitely noted however, and that was that the corona loss was less for the lower temperatures. This is as might be expected because the density of the air increases with a decrease in temperature. In this work time would not permit the studying of corona loss as affected by weather conditions to any great extent, besides the condition of most of the conductors under test was changing too rapidly for such studies. It is hoped that at some time in the future the effect of weather conditions on corona loss may be studied.

Corona Loss on Different Conductors

The first conductor tested was a 0.91-in. diameter rope-lay weathered copper cable. (See appendix for a description of these conductors.) This conductor had been in use on the 220-kv. Pit River line of the Pacific Gas and Electric Co. for several years. A section 2200 ft. long had been taken off the line especially for this test. As the conductor was removed from the towers it was carefully wrapped with strips of burlap in order to preserve the condition of its surface. In raising the conductor on the test line the burlap was not removed until the conductor had cleared the ground. To aid in the determination of the change in corona loss due to weathering, a new conductor of the same kind was next tested. (See Fig. 4)

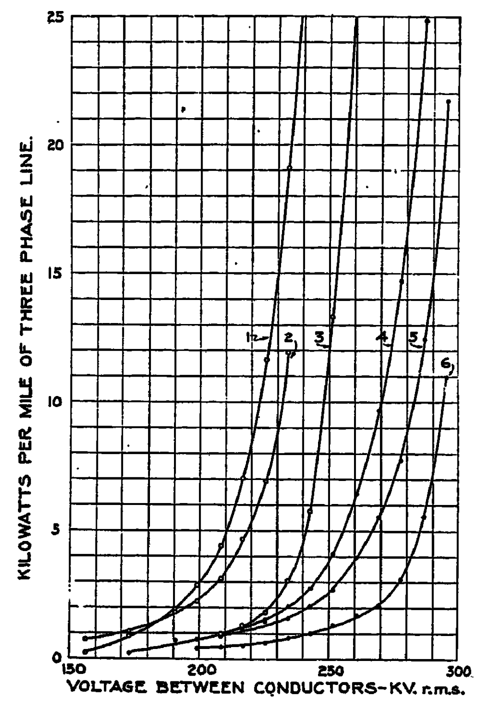

Fig. 4—Corona Loss Curves

CONFIGURATION—20 FT. HORIZONTAL BY 30 FT. MIN. TO GROUND

Curve No.	Conductor	Date	Humidity per cent	Temp. deg. fahr.	Barometer in. hg.	Remarks
2	0.91 in. rope lay copper weathered	Mar.31,1930	63	53	29.85	
1	0.91 in. rope lay copper new	Apr.30,1930	36	72	29.68	Before washing
3	0.91 in. rope lay copper new	May 1, 1930	52.5	67.5	29.90	After washing
4	1.0 in. steel core aluminum weathered	May29,1930	40.5	65	29.91	
6	1.0 in. steel core aluminum unused	May23,1930	35	80	29.94	After washing
5	1.0 in. steel core aluminum unused	May26,1930	57.5	63.5	30.01	After washing

It should be noted that for all the loss curves in this paper except those in Fig. 9 and Fig. 10, the corona loss per mile of a three-phase line is plotted as a function of the voltage between lines. The loss per mile of line was chosen in preference to the loss per conductor mile because the loss on the three conductors is not the same; another reason is that the engineer usually thinks of a three-phase line as a unit.

The next tests were on a new two-layer concentric hollow copper cable 0.91 in. in diameter and a new two-layer concentric hollow copper cable 1.0 in. in diameter. While this latter conductor was in place it rained during the night; a few measurements were made during the rain the next day and some immediately after; the losses during the rain were rather high but the rainfall was not steady enough to obtain a good loss curve. The curve in Fig. 5 shows the variation in loss at 220 kv. from the beginning to the end of a short shower. No measurement was made of the rate of rainfall. The loss measurements made on this conductor the day after the rain showed the loss to be much higher than before the rain. (See Curves 1 and 2, Fig. 6) Evidently some change had taken place on the surface of the conductor. The new copper conductors were somewhat greasy, apparently left that way from some process of their manufacture. Since the rain had made such a definite increase in the losses on the new conductor it was decided to see what effect washing it would have. The process of washing was as follows: The line was

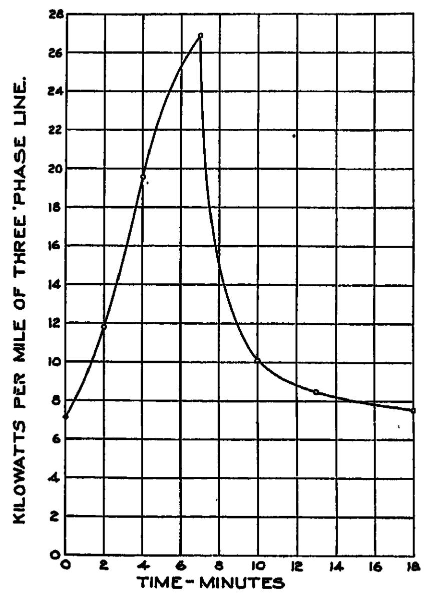

Fig. 5—Corona Loss During Shower at 220 Kv. Between Lines

Conductor— 1.0 in. hollow concentric two layer copper
Date— April 14, 1930
Humidity— 100 per cent
Temperature—58 deg. fahr. (taken in the laboratory)
Barometer— 30.05 in. hg.

lowered and the conductors were supported on wooden horses. The cables were then scrubbed with gasoline, the excess gasoline being wiped off and the rest allowed to evaporate. This was followed by a scrubbing with

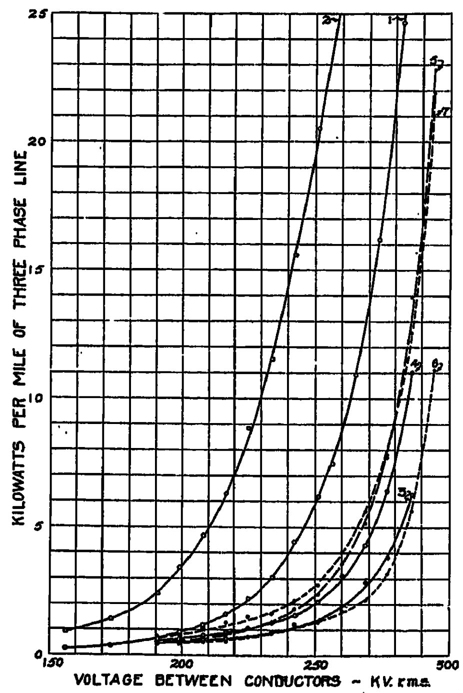

FIG. 6—CORONA LOSS CURVES

CONFIGURATION—20 FT. HORIZONTAL BY 30 FT. MIN. TO GROUND

Curve No.	Conductor	Date	Humidity per cent	Temp. deg. fahr.	Barometer in. hg.	Remarks
1	1.0 in. hollow concentric two layer copper	Apr. 11, 1930	45	69	29.96	Before washing
2	1.0 in. hollow concentric two layer copper	Apr. 15, 1930	59	63.5	30.05	After rain
3	1.0 in. hollow concentric two layer copper	Apr. 23, 1930	52	68	29.90	After washing
4	1.0 in. hollow concentric two layer copper	Apr. 28, 1930	59.5	62.5	30.00	After washing
5	1.0 in. steel core aluminum (unused)	May 21, 1930	26.5	69.5	30.16	Before washing
6	1.0 in. steel core aluminum (unused)	May 23, 1930	35	80	29.94	After washing
7	1.0 in. steel core aluminum (unused)	May 26, 1930	57.5	63.5	30.01	After washing

soap suds which were washed off by means of a cloth and plenty of clean water. To remove any further traces of soap that might be left the conductors were again washed with running water and scrubbing brushes. The line was then raised into place and when dry was tested. The scrubbing brushes used in all this washing process were of the common variety with fiber bristles.

The surprising thing was, that while the rain had left this conductor in a condition such that the losses were higher than those before the rain, the effect of the washing was to reduce the losses to less than those before the rain. (See curves in Fig. 6) The condition of the conductor was carefully inspected before and after washing and the only visible effect that the scrubbing

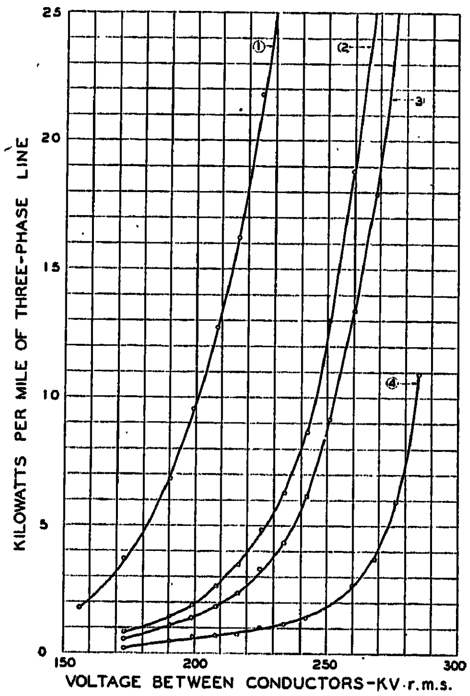

FIG. 7—CORONA LOSS CURVES

CONFIGURATION—20 FT. HORIZONTAL BY 30 FT. MIN. TO GROUND

Curve No.	Conductor	Date	Humidity per cent	Temp. deg. fahr.	Barometer in. hg.	Remarks
1	1.0 in. hollow concentric single layer copper	May 12, 1930	57	64	30.04	Before washing
3	1.0 in. hollow concentric single layer copper	May 14, 1930	60	60	30.02	After washing
2	0.91 in. hollow concentric two layer copper	May 7, 1930	46	60	29.99	Before washing
4	0.91 in. hollow concentric two layer copper	May 8, 1930	33	64	29.87	After washing

seemed to have was to remove some of the stains which had been left by the rain. The strands of this particular conductor were very free from slivers and burrs. A week later when the line was taken down it was noted that the copper had oxidized much more rapidly after washing than before, indicating that the grease had been protecting its surface. Measurements made a few days after the conductor was washed showed a

slight increase in losses above those measured immediately after washing. (See Curve 4 of Fig. 6)

The other two new conductor specimens, the 0.91 rope-lay and 0.91 concentric, that had already been tested and taken down were again put up and tested, lowered and washed in the same manner just described, and then were raised and tested again. The results are shown in the curves of Fig. 4 and Fig. 7. The next conductor to be mounted on the line was a single-layer concentric hollow copper cable 1.0 in. in diameter. The strands of which this conductor was composed were rather large. (See appendix for description.) Apparently during manufacture these strands were scored,

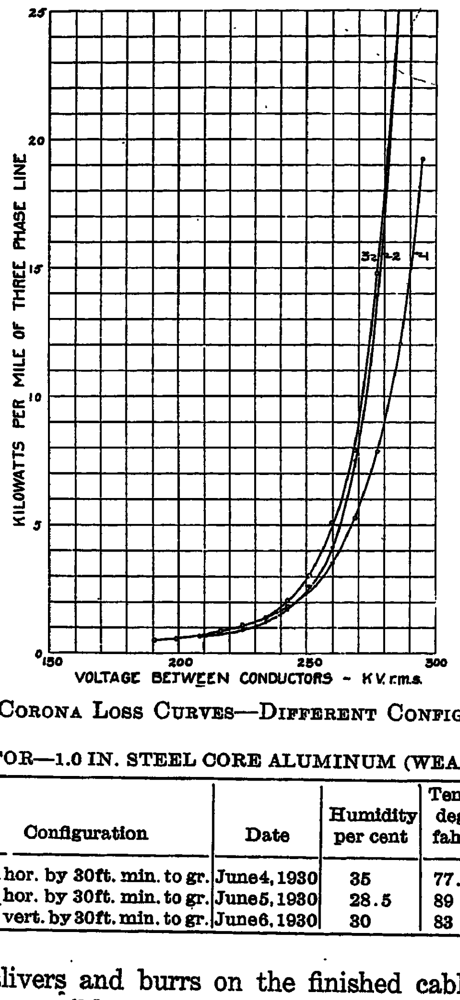

FIG. 8—CORONA LOSS CURVES—DIFFERENT CONFIGURATIONS

CONDUCTOR—1.0 IN. STEEL CORE ALUMINUM (WEATHERED)

Curve No.	Configuration	Date	Humidity per cent	Temp. deg. fahr.	Barometer in. hg.
1	20ft. hor. by 30ft. min. to gr.	June4, 1930	35	77.5	30.00
2	15ft. hor. by 30ft. min. to gr.	June5, 1930	28.5	89	29.96
3	15ft. vert. by 30ft. min. to gr.	June6, 1930	30	83	29.83

leaving slivers and burrs on the finished cable which makes impossible a fair comparison between this conductor and the other one inch copper conductor made up of smaller strands. It is interesting to note that the losses on this conductor before washing were much greater than any of the others. Washing greatly reduced the loss; however, it was still high. See Fig. 7. Just how much of this increase in loss above that of the other one inch concentric copper conductor was due to the larger strands, of which the cable was composed, is still a question, because while the process of washing removed practically all the slivers, the strands themselves were still rather badly burred.

The next specimen tested was a new concentric-lay aluminum conductor 1.0 in. in diameter. This cable was not quite in the same condition as it was when it left the factory. Evidently care had not been taken in the handling before it had reached the laboratory. The cable was somewhat scratched and dirty, so that the loss curves are not exactly what they would be for a similar conductor direct from the factory. However, when this conductor was washed its condition was comparable with that of the one inch two-layer concentric copper. From curves 3 and 6 in Fig. 6 it can be seen that the loss on these two conductors was practically the same immediately after washing.

The next conductor tested was one like the above except that it had been in use on the Pit River line for several years at 220 kv. It was taken down at the same time and handled in the same way as previously described for the weathered rope lay copper conductor.

LINE CHANGES

Up to this time all the tests had been made with all three conductors in the same horizontal plane with a spacing of 20 ft. a sag of 8 ft., and a minimum clearance to ground of 30 ft. The next test was with the weathered aluminum with the conductors in horizontal configuration, having a spacing of 20 ft., at three different elevations beginning with 70 ft. clearance to ground, followed by tests at 30 and 20 ft. clearances. The losses with the line at these three elevations were practically the same, the differences being so small that it seemed unnecessary to show the three curves.

The spacing between conductors was then changed from 20 ft. to 15 ft. with a clearance to ground of 30 ft. The results are shown in curves 1 and 2 in Fig. 8. The conductors were then supported vertically all in the same plane with a 15 ft. spacing and a clearance to ground from the lower conductor of 30 ft. The loss curve is shown in curve 3, Fig. 8.

As can be seen from the curves there is not much difference in loss for the different spacings and configurations. This is as might be expected because the electric field about the conductor is the resultant of the field to ground and the field between conductors. Since the field to ground is at a different phase angle to that between conductors, changing the distance between conductors alters only one component of this field; the same is true with respect to changing the distance of the line to ground. Furthermore the field intensity varies only as the logarithm of the dimensions.

WATTMETER READINGS AND CHARGING CURRENTS

With the three conductors in the same plane the loss on the center one is greater than on either of the outside conductors, because the electric field intensity is greater on the center wire. In this paper no attempt has been made to determine the loss on each conductor separately. For those who are interested in this, the

curves in Fig. 9 and Fig. 10 show what is apparently the loss on each conductor for different configurations. This "apparent loss" was computed from the wattmeter readings in the ordinary manner by multiplying the reading of the wattmeter instrument by the multiplying factor computed for the water resistor wattmeter multiplier. It will be noted that with the three conductors in the same horizontal plane the apparent

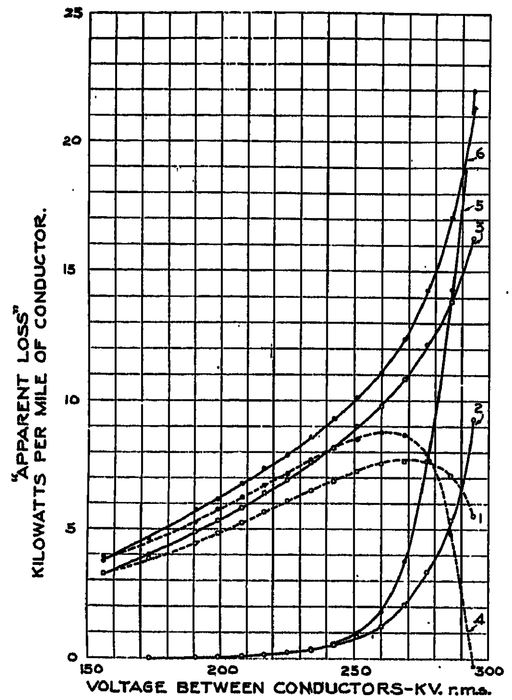

FIG. 9—CURVES, SHOWING "APPARENT LOSS" ON EACH PHASE FOR 20 FT. AND 15 FT. HORIZONTAL SPACINGS

CONDUCTOR—1.0 IN. STEEL CORE ALUMINUM (WEATHERED)

Curve No.	Configuration	Date	Humidity per cent	Temp. deg. fahr.	Barometer in. hg.	Phase
1	20 ft. hor. by 30 ft. min. to gr.	June4,1930	35	77.5	30.00	1
2						2
3						3
4	15 ft. hor. by 30 ft. min. to gr.	June5,1930	28.5	89	29.96	1
5						2
6						3

loss for one of the outside conductors is negative, while for the other outside conductor the apparent loss has a large positive value and the loss shown for the center conductor is approximately the actual loss. The algebraic sum of the apparent losses for the three conductors at any particular voltage is the actual loss for the three-phase line at that voltage. This is because the power in this three-phase neutral grounded circuit is measured with three wattmeters. It is interesting to note that the algebraic sum of the apparent loss on the two outside conductors divided by two is almost equal to that shown for the center conductor. If the line could be suspended high enough so that the ground had no effect on it and if the three conductors were equidistant from each other the charging currents would all be equal and 120 deg. apart; the loss on the three conductors would be the same and the three wattmeters would read alike. Of course this condition is far from that met with in practise. The complete vector diagrams and explanations of the circuits used in this work would be almost material enough for another paper. Mr. R. J. C. Wood gives a very good explanation of some of this in his paper listed in the bibliography.[2]

When the conductors were all mounted in the same vertical plane the phase rotation of the line was changed giving an entirely different distribution of wattmeter readings. However, the losses computed from these were practically the same as before so this curve is not

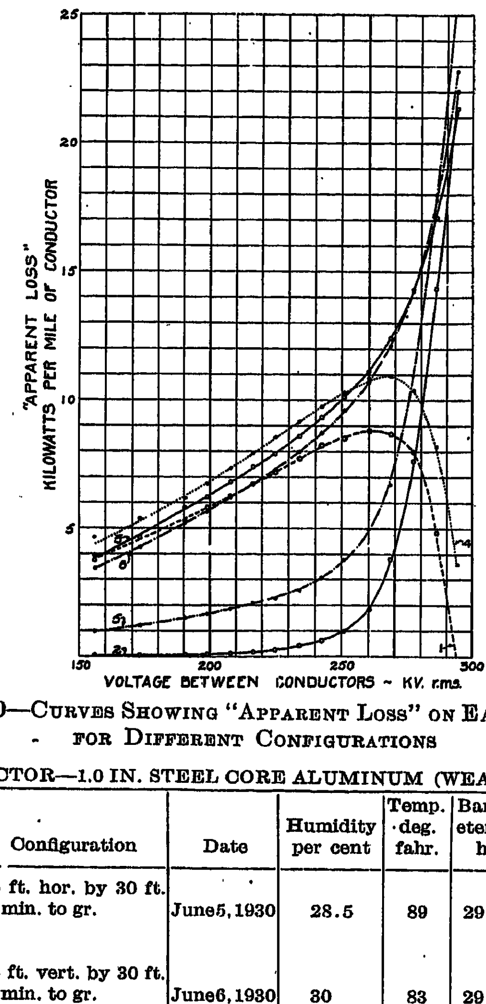

FIG. 10—CURVES SHOWING "APPARENT LOSS" ON EACH PHASE FOR DIFFERENT CONFIGURATIONS

CONDUCTOR—1.0 IN. STEEL CORE ALUMINUM (WEATHERED)

Curve No.	Configuration	Date	Humidity per cent	Temp. deg. fahr.	Barometer in. hg.	Phase
1	15 ft. hor. by 30 ft. min. to gr.	June5,1930	28.5	89	29.96	1
2						2
3						3
4	15 ft. vert. by 30 ft. min. to gr.	June6,1930	30	83	29.83	1
5						2
6						3

shown in this paper. For the curves shown in Fig.10 the phase rotation of the line was tested and found to be in the same order as the numbering of the conductors. The curves shown in this paper are all plotted from data taken with this phase rotation.

Corona loss curves taken immediately after each of the five conductors were washed are shown in Fig. 11. It is believed that the surface conditions of the conductors were more nearly alike during these tests and hence these curves offer the fairest comparison of the conductors.

Fig. 12 shows some of the corona loss data plotted on semi-logarithmic cross section paper. The study of the slopes of the different curves is rather interesting.

Charging currents to the line were measured and when plotted against line voltage gave practically

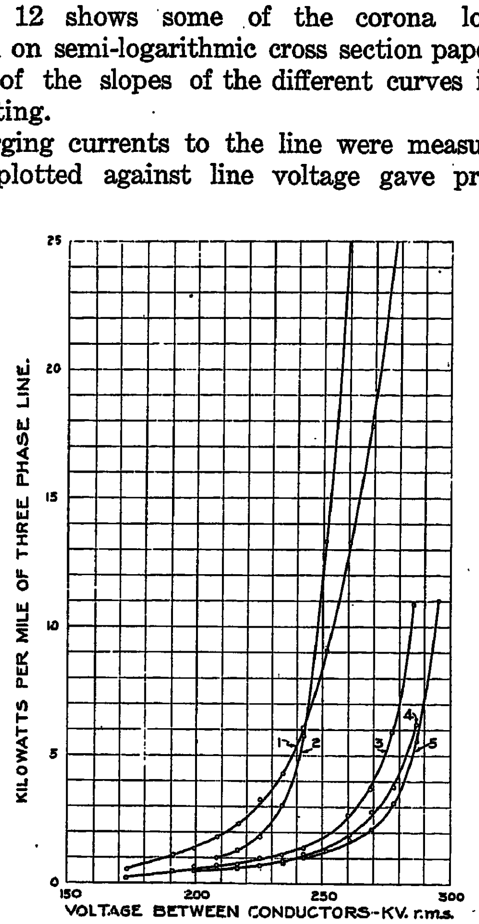

FIG. 11—CORONA LOSS CURVES—WASHED CONDUCTORS

CONFIGURATION—20 FT. HORIZONTAL BY 30 FT. MIN. TO GROUND

Curve No.	Conductor	Date	Humidity per cent	Temp. deg. fahr.	Barometer in. hg.
1	1.0 in. hollow concentric single layer	May 14, 1930	60	60	30.02
2	0.91 in. rope lay	May 1, 1930	52.5	67.5	29.90
3	0.91 in. hollow concentric two layer copper	May 8, 1930	33	64	29.87
4	1.0 in. hollow concentric two layer copper	Apr. 23, 1930	52	68	29.90
5	1.0 in. steel core aluminum used	May 23, 1930	35	80	29.94

straight line curves. The values of charging currents for different conductor configurations are shown in the following table for a voltage between lines of 220 kv. and a minimum clearance to ground of 30 ft.

Configuration	Spacing	Conductor	Charging current per mile of conductor
Horizontal..........	20 ft.	Outside	667 milliamperes
		Center	717
		Outside	675
Horizontal.........	15 ft.	Outside	694
		Center	754
		Outside	705
Vertical.............	15 ft.	Top	690
		Center	758
		Bottom	709

The power factor computed for the line, when the washed aluminum conductor was used, was less than one-quarter of one per cent at 220 kv.

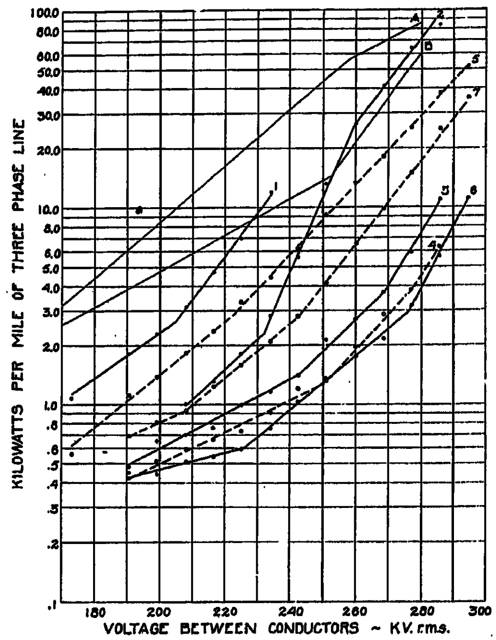

FIG. 12—CORONA LOSS CURVES

CONFIGURATION—20 FT. HORIZONTAL BY 30 FT. MIN. TO GROUND

Curve No.	Conductor	Date	Humidity per cent	Temp. deg. fahr.	Barometer in. hg.	Remarks
1	0.91 in. rope lay copper weathered	Mar.31,1930	63	53	29.85	
2	0.91 in. rope lay copper new	May 1, 1930	52.5	67.5	29.90	After washing
3	0.91 in. hollow concentric two layer copper	May 8, 1930	33	64	29.87	After washing
4	1.0 in. hollow concentric two layer copper	Apr. 23, 1930	52	68	29.90	After washing
5	1.0 in. hollow concentric single layer copper	May14.1930	60	60	30.02	After washing
6	1.0 in. steel core aluminum unused	May23,1930	35	80	29.94	After washing
7	1.0 in. steel core aluminum weathered	May29,1930	40.5	65	29.91	

Curve	Conductor	Configuration	Remarks
A	0.91 in. rope lay copper	19 ft. horizontal by 30 ft. min. to ground	Data from Wilkins[4]
B	1.0 in. steel core aluminum	19 ft. horizontal by 30 ft. min. to ground	Data from Wilkins

Comparison of this work with that done by others has been purposely omitted on account of space limitation. A bibliography is given at the end of this paper for those not acquainted with such work.

Conclusions

The results of the tests show that the corona loss on new cleaned conductors is the same for copper as it is for aluminum.

The effect of weathering of the conductors, as received from the factory, was such as to decrease corona loss, while the effect of weathering of the new conductors after washing was to increase the loss.

Corona loss over the operating range of voltage of a 220-kv. line is affected only slightly by a considerable change in conductor spacing or configuration, or clearance to ground.

Until further tests are made the use of strands as large as those of the one inch single-layer hollow copper conductor, on a one inch conductor, for 220 kv. will be questionable.

While the loss on the washed 0.91-in. hollow concencentric copper conductor is very low at 220 kv. the use of such a cable is not recommended for a 220-kv. line because there is not sufficient margin to allow for the increased loss at higher altitudes and for the accumulation of dirt.

The losses on a rope-lay conductor are greater than on a concentric-lay cable of the same diameter.

The amount of decrease in corona loss by washing a new conductor would seem to justify the removal of the grease on the conductor at the factory rather than wait for the weather to do this at a considerable loss of power.

Acknowledgments

The authors are indebted to Dr. Harris J. Ryan for his helpful advice and suggestions.

The tests described in this paper were made possible through the cooperation of the Pacific Gas and Electric Company.

The hollow aluminum conductor used for the shielded wattmeter lead was donated to the laboratory by the Aluminum Company of America.

The three specimens of hollow copper conductor used in these tests were contributed by the Anaconda Wire and Cable Company and are to be left at the laboratory.

Appendix

Description of Conductors

Rope-Lay Conductor 0.91 in. Diameter. This conductor is made up of seven large strands, each of which is made up of seven wires 0.101 in. in diameter with a left hand lay and a pitch of 5 in. The seven large strands have a right hand lay and a pitch of 15 in. There were two specimens of the above conductor, one new and one which had been in use on the 220-kv. Pit River line of the Pacific Gas and Electric Co. for several years.

Two-Layer Concentric-Lay Hollow Copper Conductor, 0.91 in. Diameter. There were 24 wires in the outer layer 0.101 in. in diameter. The pitch of this layer was approximately 12 in. The inner layer was made up of 14 wires 0.125 in. in diameter. The core consisted of two rubber covered pilot wires. (This conductor was made up especially for these tests and is not a commercial cable.)

Two-Layer Concentric-Lay Hollow Copper Conductor, 1.0 in. Diameter. This conductor was composed of 50 wires 0.097 in. in diameter. The 28 wires in the outer layer had a pitch of approximately 11 in. The core of the cable was a twisted copper *I*-beam.

Single-Layer Concentric-Lay Hollow Copper Conductor, 1.0 in. Diameter. This one layer was made up of twelve wires 0.196 in. in diameter and had a pitch of approximately 8.5 in. The core was a twisted copper *I*-beam.

Two-Layer Concentric-Lay Steel Core Aluminum Conductor, 1.0 in. Diameter. This conductor was composed of 42 aluminum wires 0.112 in. in diameter. The 24 wires in the outer layer had a pitch of approximately 11 in. The core consisted of 19 strands of 0.111 in. diameter steel wire.

The area of the cross section of each of the above described conductors, with the exception of the 0.91 in. concentric-lay hollow copper was approximately 500,000 circular mills.

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Discussion

L. V. Bewley: A great amount of work has been done in the past on corona loss at normal power frequencies. We are now entering an era where it is of increasing importance to know something about the laws of corona under transient, and particularly traveling wave conditions. This requirement is occasioned by the study of abnormal surges on transmission lines, and means of protection against them. Corona losses are responsible for the rapid attenuation and distortion of high-potential traveling waves. The attenuation is known to be extremely sensitive to weather conditions, wave shape, polarity and voltage, and varies over a wide range, even for the same line. However, these separate effects have not been evaluated, nor has the law of corona been established for traveling waves. Therefore, from the point of view of transmission system protection, it would seem advisable for the experimenters to pay some attention to *transient* corona loss. A knowledge of the law which governs these losses may point the way to at least the partial control of dangerous traveling waves.

A. O. Austin: Anyone who has not made tests to determine corona loss can hardly appreciate the amount of time, effort, and expense required to obtain the information disclosed in the paper.

The various factors affecting corona are too complicated to be

covered by a simple formula except for a very limited range, hence we must depend upon measurements for losses. At the present time there is need for information on the larger conductors covering a considerable difference in the size of wire. Laws which may hold for a small conductor may be misleading for the large sizes of conductor and it is hoped that the work at the Ryan Laboratory will be continued.

Owing to the high reactive drop at 60 cycles, it is advisable to use higher voltages for many installations in order that the capacity per circuit in kilowatts may be increased and the cost of transmission reduced.

Information such as that included in the paper is, therefore, very valuable in making it possible to work within narrow limits.

Corona is not only a loss in power but in recent years has been a source of radio interference which must be carefully watched. In fact radio interference may become a factor in determining the size of a conductor on many lines rather than loss from corona. This is particularly true where the amount of power transmitted will not require a large conductor, such as in taps from large trunk lines. There are many transmission lines in operation in which corona is a source of radio disturbance. Where these lines were installed in advance of radio reception, complaints have not been serious. Where, however, a new line is located in a moderately or thickly populated district, serious complaints are likely to result if the conductor size is too small.

It is possible that a conductor having a rather high corona loss may not be as serious a source of radio interference as a larger conductor with less corona loss. In the large conductor, the corona or discharge starts only after there is considerable potential on the conductor, hence the radio disturbance may be more severe than for a smaller conductor which discharges initially at a relatively low voltage on the wave. For a large range of conductor sizes, however, it would appear that the magnitude of the radio disturbance curves will be approximately the same as that for corona losses shown in the paper. Fig. 1 shows such a series of tests run on several different sizes of conductor.

In order to show that the disturbance is due to a discharge on the positive wave, a series of tests was run under the conditions in Fig. 1 by using one large conductor which would be well above the corona point. Fig. 2, A, B, and C show the disturbances as indicated by oscillograms.

It is possible that some method may be devised which will make it possible to determine the corona loss by a radio interference method as a means of supplementing work similar to that carried out in the Ryan laboratory.

The oscillograms show that the radio interference from a coated conductor Fig. 3 has been greatly reduced. Since a slightly increased dielectric strength in the air will greatly increase the corona point, it is evident that a coating having a slight increase in dielectric strength over that of the air may be very beneficial in reducing corona loss or radio interference. Figs. 2 and 3 show the comparison between a plain and a coated conductor in which it will be seen that radio disturbance and corona loss have been materially controlled. Fig. 4 shows two types of coated conductor one with control or projecting strands and the other with all strands coated with insulating paint or varnish.

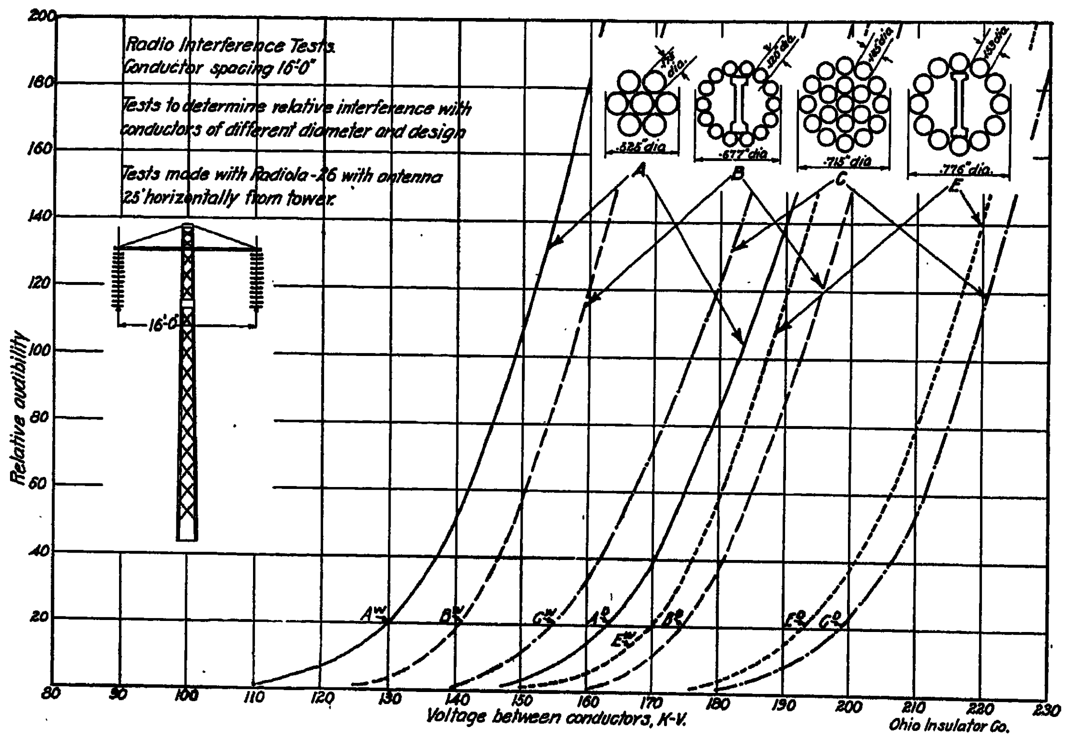

FIG. 1

It is possible that conductors of this kind may find a use in clearing up radio trouble or for operating at very high voltages or at high altitudes, as means have been worked out for coating conductors in place.

Longer transmissions at higher voltages make information as to corona losses far more important than in the past and it is hoped that the work at the Ryan Laboratory will be extended as the information is of great economic importance to the transmission industry.

R. S. Daniels: In November, 1929, we put in operation, 65 miles of 130-kv. line, and almost immediately experienced serious radio trouble. This trouble disappeared considerably in about three months from no reason that could be accounted for, other than that it was due to corona which in the meantime had decreased.

The noise was readily detected from the ground by ear, and was about the same in the middle of a span as at the supports. This was checked on a span over 2000 ft. long, where the observer was about the same distance from the conductor when in the center of the span as when at the foot of the towers.

The conductor was Anaconda composite, stranded cable 2/0 conductivity, with a three-strand bronze core. At one end the line joined an old line of 2/0 copper, operating at the same voltage. Both lines were similarly insulated and constructed on wood "H" frames, and no similar noise was observed under the old line.

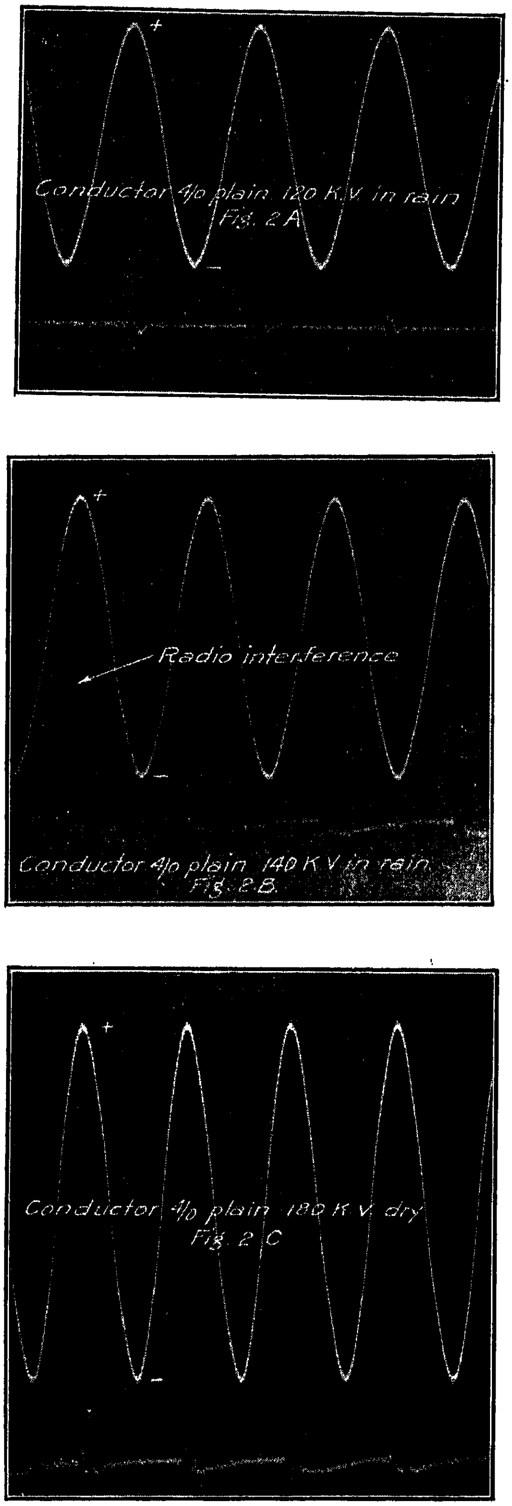

Fig. 2

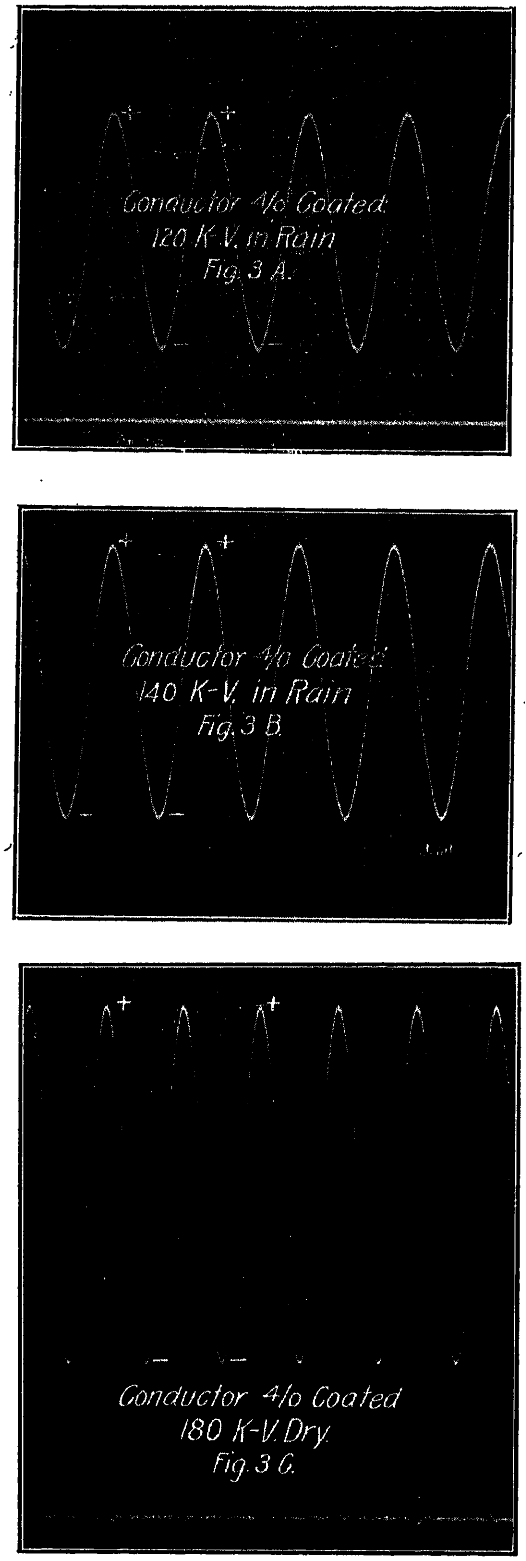

Fig. 3

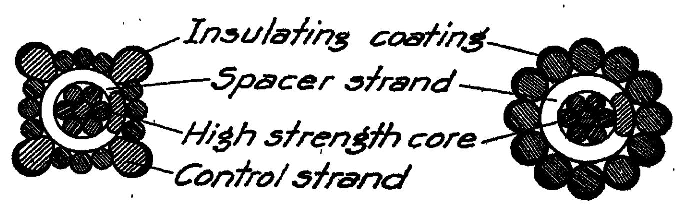

Fig. 4

E. Van Atta: It has been shown in this paper that corona losses were increased due to rain and that these losses remained

high after the conductors had dried off. This fact is rather mystifying.

J. B. Whitehead: Corona begins on a smooth round wire at a definite value of surface voltage gradient, dependent on the pressure and temperature of the air. Corona energy loss is due principally to the frictional motion of gaseous ions formed in the corona through the air towards the opposite conductor. The magnitude of the loss depends on the number of ions generated, their size, the distance they travel, their specific mobilities, and on the temperature, pressure, and moisture content of the air.

The lack of uniformity and of definite indications of the results given in the paper by Messrs. Carroll, Brown, and Dinapoli is due to the impossibility of controlling or even measuring all of the factors which enter. The surface conditions of conductors are irregular, unknown, and uncontrolled. Corona begins at local spots and increases irregularly, the sizes and mobilities of the ions vary with the atmospheric conditions in an unknown way, and the length of travel of space charge is uncertain in the unsymmetrical arrangement of the conductors.

The same uncertainty has characterized all measurements of corona loss on lines in the open since those of Mershon, who first emphasized the unknown influence of atmospheric conditions. Peek has attempted to take account of some of the unknown variables by the introduction of empirical constants into his formulas, but they do not cover all the factors entering, and the results of Ryan, Harding and others show only approximate agreement.

The results of the present paper will have a certain value as the first measurements at 220 kv. It is regrettable, however, that so elaborate and carefully developed a measuring equipment should yield such indefinite results. In the writer's opinion the greatest value is in the indication that corona loss can never be definitely computed in advance until a greatly simplified conductor surface is adopted, and the laws of the influence of atmospheric conditions are uncovered by controlled experimentation.

Development of the Porcelain Insulator

BY K. A. HAWLEY*

Member, A. I. E. E.

Synopsis.—*Porcelain insulators have been manufactured and used for the transmission of high-tension electric power for forty years. The first designs were of the single-piece and multipart cemented pin type. Necessity for higher safety factors against flash-over and increase in operating voltages demanded a rapid increase in the size of the insulators. This reached an economic limit at the operating voltage of 66 kv. The suspension unit overcame this temporary check of increased operating voltage.*

Further study of the electrostatic capacitance of the various parts and consequent voltage distribution, made marked refinements in the pin type insulator possible. During this time the single-piece porcelain suspension unit took practically its present form.

Early improvements were the provision of proper expansion joints and the separation of the lip of the cap from the porcelain hood.

Gradual improvements have since been made resulting in a great increase in mechanical strength. These changes have been principally in hardware design. By experiment and analysis the shapes of the cap and pin have been determined to give a uniform distribution of load from the pin to the cap. Constant check tests by the quick pull and time loading methods have shown that the suspension insulator with properly designed hardware and a suitable coating on the cap to prevent the cement from adhering to the metal, has a high strength associated with electrical reliability.

Ceramic research and exact manufacturing control has made possible the production of non-absorbent, thoroughly vitrified porcelain of consistent strength. This has centered largely about the proper firing of the clay.

Recent experiments upon the properties of the combination of porcelain and glaze has eliminated surface stress and consequently assured stronger, longer lived porcelain. Still greater uniformity has been gained by glazing the sanded surfaces.

The elimination of the abutting joint and the proper design of the cemented joint has stopped expansion troubles. Proper use of Portland cement has resulted in insulators able to withstand drastic temperature changes without harm. A recent improvement in the pin type insulator is the metal threaded pin hole. This has lessened manufacturing and construction difficulties and in addition, due to the exact fit of the insulator on the pin, overcomes hidden corona and the consequent radio interference.

* * * * *

PORCELAIN insulators for the transmission of high-tension electric power have been made and used for a period of approximately forty years. Progress in their design and manufacture can be divided into ten year periods.

The last decade of the nineteenth century marked practically the beginning of electric transmission in America and also the beginning of the continuous manufacture of porcelain insulators. Insulators of this decade were all of the pin type, both single-piece and multipart cemented types. Many of these old insulators are still in use, although rarely at the operating voltages for which they were originally designed. The safety factor against flash-over was rarely sufficient for practical requirements so where the voltage has remained the same larger insulators have in most cases been substituted.

During the first ten years of the twentieth century pin type insulators advanced rapidly in size. Even at this early date it has reached its maximum economical size. For 66,000-volt transmission, pin type insulators proved to be quite satisfactory, but since the cost of the insulator varies as a power of its rating larger insulators of this type were not practical from a cost standpoint. The suspension insulator was the logical outcome of this temporary check. Comparison of the present pin type insulators shows that the cost is proportional to the 2.6 power of its flash-over value. The suspension insulator, however, offers a resistance to flashover in direct proportion to the string cost. Plotting separate cost curves for equal arc-over values show that the curves cross at approximately the 66,000-volt operating range. This corresponds very closely to the usual practise and for the higher voltages the suspension insulator has almost invariably been used.

During the next decade from 1910 to 1920, marked refinements in the pin type insulator were made. The earlier insulators were little more than porcelain cups cemented together with but a slight understanding of voltage division.[1] The division of voltage is inversely proportional to the electrostatic capacities of the respective parts. These in turn are proportional to the adjacent conducting surfaces upon the porcelain, the cement being a conductor. As these surfaces were generally small on the central and top shells, these two parts carried most of the voltage. By careful study this condition was rectified and the correct balancing of the pin type insulator was one of the decided advances of this period.

During this decade the suspension insulator took practically its present form. The unit using two pieces of porcelain, while in many ways satisfactory, necessitated a larger head diameter and a correspondingly large size of metal cap. The single porcelain unit removed these unsatisfactory features and was accordingly almost universally adopted.

Experience promptly pointed out necessary refinements. Proper expansion joints were provided and the cap which originally had been allowed to rest on the porcelain was lifted, so that under all conditions it stayed clear of the hood. (Fig. 1.) With these improvements practically all field failures stopped. Insulators even of the largest size have established a perfect life record over a period of fifteen years.

During the ten years just completed there has been a

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Presented at the Pacific Coast Convention of the A. I. E. E., Portland, Oregon, Sept. 2-5, 1930.

1. *Insulator Depreciation and Effect on Operation*, A. O. Austin, A. I. E. E. TRANS., 1914, p. 1731.

decided improvement in the suspension insulator. This improvement is not the result of any radical changes but has been rather a matter of refinements of design and manufacture. Slight changes in hardware shape, for example, have resulted in a more uniform distribution of the load delivered to the shell with a consequent greater uniformity and higher average mechanical strength. The desirability of such improvements is constantly evident. Unexpected loads greatly in excess

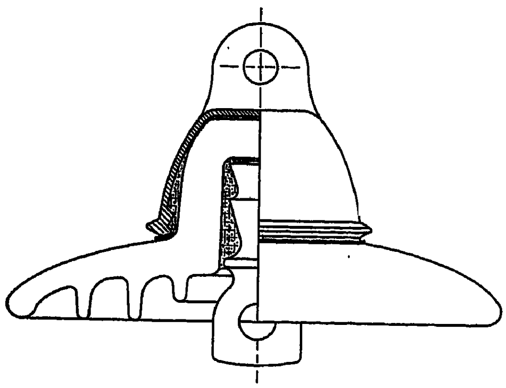

FIG. 1—EARLY 10-INCH SUSPENSION UNIT WITH EXPANSION JOINT AT EDGE OF CAP

of maximum calculated loads have been encountered and the strength of the insulator has been exceeded.[2] Three such failures upon insulators of the old type have occurred in the past two years in widely separated localities.

It was at one time thought that the strength of the insulator was limited by the strength of the standard cement used, breakage resulting in loading tests from crushing and shearing of the cement and resulting in unfavorable loads on the porcelain. This is not so. A

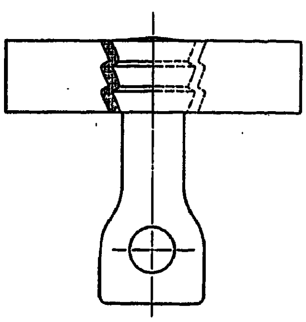

FIG. 2—EYE BOLT CEMENTED INTO STEEL RING FOR A TENSION TEST OF CEMENT STRENGTH

standard pin when cemented into a metal ring held consistently loads as high as twice the breaking strength of the insulator.

Following this a cup of porcelain was prepared representing the head of an insulator. Into this a standard pin was cemented in the usual manner and the cup was then supported on its lower edge on a metal ring.

2. *Transmission Line Construction in Crossing Mountain Ranges*, M. T. Crawford, A. I. E. E. TRANS., 1923, p. 970.

When pulled in this manner the standard pin was broken before it could be pulled from the cup. There was no evidence of bursting the cup unsupported except at its lower edge.

Following the many efforts to improve the pin shape, attention was directed to the cap. An analysis based upon directions of stress from cap to pin indicated possibilities of improvement. Changes in caps were made by filling the cap with babbitt and turning to the desired shape and as high as fifty per cent increase in combined electrical and mechanical strength resulted.

These caps when copied in malleable iron, however, showed no such improvement in performance. A close scrutiny of the previous tests on the caps containing the babbitt showed that under strain a slight slipping took place between the cap and the cement. Evidently the malleable iron caps must also be made to yield upon the cement. This research led to the painting of the inside surfaces of the cap with a suitable coating to prevent the

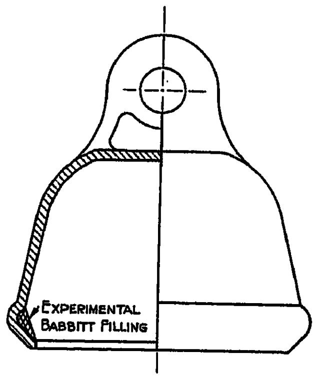

FIG. 3—CAP WITH BEARING SURFACE FILLED WITH BABBITT TO DESIRED ANGLE

cement from adhering to the metal. When this was done the desired results were obtained.

It was soon recognized that strength in quick pull-off was not always an indication of reliability. High strength against pulling apart must be associated with electrical reliability. The comparison of various available standard rated insulators brought interesting results. The insulator that had been heralded as the strongest showed on time test the earliest electrical failure. The following table shows this in detail.

The last two columns in the table show the results of the previous research. The provision of a yielding abutment to the arch of the insulator with no changes otherwise had greatly strengthened the unit. By no known test could any hazard be shown.

Since then, constant checks and rechecks with slight changes in shapes have further improved the insulator. All such changes have been tried first by the quick pull (A. I. E. E. Standard 41-305; two thousand pounds increase per minute) and by time loadings. Such time tests are made in out-of-door frames subject to con-

TIME LOADING TESTS UPON STANDARD SUSPENSION INSULATORS

Load lb.	Insulator A		Insulator B		Insulator C		Insulator D		Insulator D revised	
	Hours held	Result	Hours held	Result	Hours held	Result	Hours held	Result	Hours held	Result
	String of 6		String of 6		String of 6		String of 12		String of 6	
6,000	150	O. K.	216	O. K.	96 72	2 *E* 3 *E*	168	O. K.	192	O. K.
7,000	168	O. K.	15	*M*	144 24	3 *E* 4 *E*	15	*M*	168	O. K.
8,000	48	*M*			96	4 *E*			168	O. K.
9,000					240	4 *E*			168	O. K.
10,000					168	5 *E*			24	*M*
11,000					168	5 *E*			24	*M*

E—Electrical failure. Numeral indicates total number failed.
M—Complete mechanical failure of one unit in string.

siderable vibration and all changes of the weather at both Victor, New York and Baltimore, Maryland.

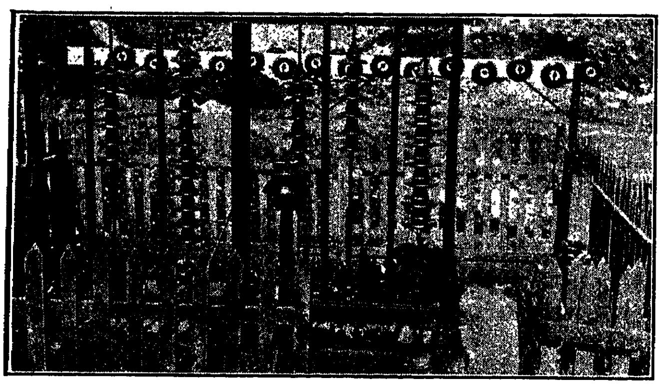

FIG. 4—OUTDOOR FRAME AT VICTOR

Outdoor loading frame for suspensions, levers and weights, used. Standard strength units carrying 5000 lb. and intermediate carrying 12,000 lb. since September 1927. All still sound.

In addition to this, periodical check tests are regular routine. Sample check test report follows:

PERIODICAL CHECK TEST

A. Puncture (A. I. E. E. Standards 41; 153) (1) 145,000; (2) 140,000; (3) 152,000 volts.

B. Mechanical Ultimate and Electrical Test. (A. I. E. E. Standards 41: 154). (1) 16,000; (2) 15,300; (3) 16,000 lb.

C. Combined thermal—tension test.
Water temperatures, 205 deg. fahr. and 39 deg. fahr.
Ten minutes in each alternately.
Initial load 4,000 lb., increase 1,000 lb. per cycle.
Two units tested. First failure at 12,000 lb.

D. Time loading tests. Out-of-door any weather. Initial load 8,000 lb., increase 1,000 lb. each working day.
Arced over before each increment of load.
Two units tested, first failure 17,000 lb.

Efforts have been made to distribute the load upon the outside of the porcelain more uniformly by multiple stepped caps. No advantage in any test was observed and in many cases decidedly unsatisfactory results were forthcoming. The thin metal of the cap apparently yielded so that the upper step would carry more than its share of the load. Annular ridges within the caps are of the same character and are generally worse than useless.

Similar tests upon the pin, however, have always shown advantages from the multiple stepped pin, provided such steps are above the lower edge of the insulator cap. In this case, of course, the mass of the pin is sufficient to prevent any yielding.

Most of the early porcelains were thoroughly vitrified, but only too often with an excess of flux (feldspar). The comparatively thin sections allowed quick firing and rapid cooling. Such over-fluxing and rapid cooling can only result in ware that is lacking in strength, and there is little doubt that differences in performance of individual specimens of the same type and lot of the old insulators, were largely the result of variation in strength.

Over firing to the beginning of volatilizing of some of the ingredients (ceramically known as "bloat") has rarely been the cause of trouble. In fact, experience with such ware suggests that this condition may possibly be desirable rather than hazardous.

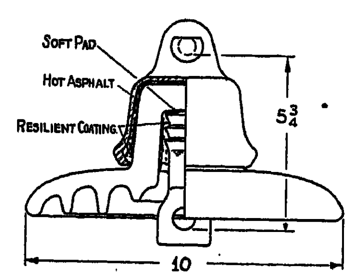

FIG. 5—MODERN CEMENTED SUSPENSION INSULATOR SHOWING PROVISION FOR EXPANSION AND YIELDING JOINTS

In some cases, under firing may have resulted in a short lived semi-vitrious ware which would be a cause of trouble. With the exact manufacturing con-

trol exercised today such conditions no longer exist and need not be considered in this discussion. The best porcelain today is recognized to be one of greater sturdiness, less flux, thorough vitrification, and careful cooling. Heavy sections have been demanded to withstand external violence, power arcs, punctures, and various forms of mischievousness. Lesser flux means greater mechanical and electrical strength, but with this reduction in flux in the thicker sections far greater care must be exercised in firing. Improper firing will invariably result in internal stress in the porcelain which seriously affects both the strength and life of the ware. Today constant thermal cycle checks are employed (A. I. E. E. Standard 41-250; 350). Such tests are largely a measure of the care used in kiln cooling. Regular porosity checks are made to insure thorough vitrification and proper coordination between all details of firing.

Recently greater strides have been made in the combination of porcelain and glaze. If the glaze covering the porcelain does not "fit" due to its coefficient of expansion being different from the porcelain it will be under stress. When this stress is above the elastic limit of the glaze crazing or crackling of the surface will be apparent. In the majority of cases, however, there are no visible cracks and yet the strains are there. Add an external load either of a mechanical nature or due to thermal changes to those already inherent in the surface of the dielectric, and small cracks will develop which will form the basis for a progressive failure of the porcelain.

Making and breaking in the testing machine comparative rods with various glazes pointed the way to the elimination of surface stress and the consequent development of stronger, longer lived porcelain. As an even more recent development, further strengths and greater uniformity have been gained by glazing the sanded surfaces.[3]

The abutting joint in the insulator assembly wherever found has been a source of trouble. As already explained, the separation of the cap of the suspension insulator from the horizontal hood has stopped losses in that type. Similar breakages occurred when the caps of switch type insulators were placed upon the porcelain so that the cement would bear upon the fillet between the head and the horizontal hood. Wherever this has been done, especially in climates where freezing occurs, there have been insulator losses. When the cap and the cement within it have been kept above this fillet these breakages have not occurred.

When the cap shrinks with cold or when free water between the cement and porcelain freezes there is a radial pressure against the fillet with an upward component. This reaction becomes a tension stress upon the porcelain—a stress which it is least able to carry.

If the cement is above the fillet the stress is entirely horizontal and becomes purely a compression force upon the porcelain. Against such stress porcelain is one of the strongest materials known.

Another form of the abutting joint is that which was used largely in pin type designs in the past. In this case the joint was between two porcelain parts. This, commonly known as the closed joint, was used chiefly for two purposes. First, such an insulator would be free from corona display at relatively high voltages, and second, the self-alining features of the closed joint offered a decided advantage in ease of factory assembly. The cause of the breakages experienced with this type of insulator was the same as with the suspension or switch type already described. The outer piece, however, in this case was generally the weaker and was usually the first to break. The edges of the upper porcelain part at the joint were frequently thin and were consequently weakened by over-firing because of this thinness.

Portland cement has been blamed for many insulator failures. It is certain that the chief complaint is not against the cement but against its improper use. It has been found that cement which will successfully pass the A. S. T. M. Soundness Test (A. S. T. M. Standard Specifications and Test for Portland Cement C9-26) is fit for insulator work. As a result special stress is laid on soundness, and every lot of cement before it is released for production is carefully checked as to this characteristic. In connection with this research, cement specimens were alternately soaked in water and frozen to − 20 deg. fahr. There was a slight contraction in the specimen corresponding to such a temperature drop. There was no increase in length which would correspond to a volume increase by formation of ice crystals. This confirms statements made by cement manufacturers that water within the colloidal structure of the cement does not freeze. Any harm done by freezing must be from free water within open voids in the cement.

Let us assume that the cement and central porcelain parts completely fill a porcelain ring outside of it. A ring of porcelain placed about an unyielding central part must shrink according to the following formula to destroy itself.

Let:—

E = Modulus of elasticity

C = Coefficient of expansion

S = Strength per unit area

t = Temperature difference

Then,

$$t = \frac{S}{E\ C} \text{ for shrinkage to cause porcelain breakage}$$

Assuming,

E = 7,500 lb. per sq. in.

C = 0.0000025 (fahr.)

S = 5,000 lb. per sq. in. (conservative)

then,

t = 267 deg. fahr.

3. D. H. Rowland, *G. E. Review*, March 1929 and June 1930.

Examination of the open type of cement joints shows that insulator failures have almost always occurred in those insulators with wide cement joints or with great cement masses, or with overfilled tapered joints.

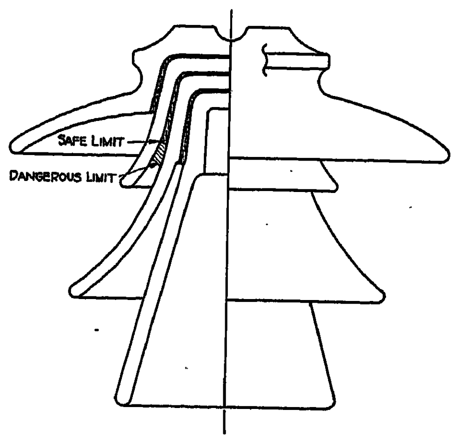

FIG. 6—SAFE AND DANGEROUS LIMITS IN CEMENTED JOINTS

All cement when drying shrinks. Mixtures which contain the smallest percentage of water are those which show the least shrinkage when drying. Such mixtures are also stronger. The use of ⅛ sand in the mix will cut down the shrinkage exactly ⅛ and make the material much more inert. When the cement shrinks against the parts within there is a tendency towards cracking of the cement. This cracking is reduced to a minimum, if not prevented entirely, if the cement joints are narrow, if the cement is dense and strong, and if it is firmly anchored in place by sanded surfaces upon both sides of it. Where insulators with these features have been found there have been no breakages.

On the other hand, where there has been an excessive

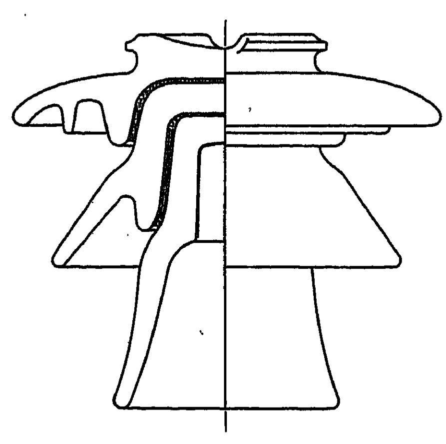

FIG. 7—PIN TYPE INSULATOR
Cement joints properly filled and proportioned

cracking of this cement or where water can find a passageway between the cement and porcelain the freezing of that water and the consequent increase in volume is frequently accompanied by a failure of porcelain. Such breakages have been observed to occur immediately adjacent to a crack in the cement as a result of localized pressure.

An examination of insulators made over a long period of time shows that they can be separated into groups, one of which may be expected to fail and the other not. This dividing line has been sufficiently sharp and close that a reasonable insulator life may now be confidently predicted. The modern insulator is made with cement joints as narrow as manufacturing tolerances will allow, while the cement used is dense and contains a minimum amount of water in the mix. The joints are not overfilled and the cement is fully set and expanded by curing at a suitable temperature in a saturated atmosphere.

One of the recent improvements in the pin type insulators has been the metal threaded pin hole. It is relatively difficult to manufacture porcelains with the thick sections demanded by modern practise. These thick sections even under the best controlled conditions do not shrink uniformly. This is chiefly due to the condition of the plaster mold. The amount of moisture in the mold varies during different hours in the day due to week end and other interruptions.

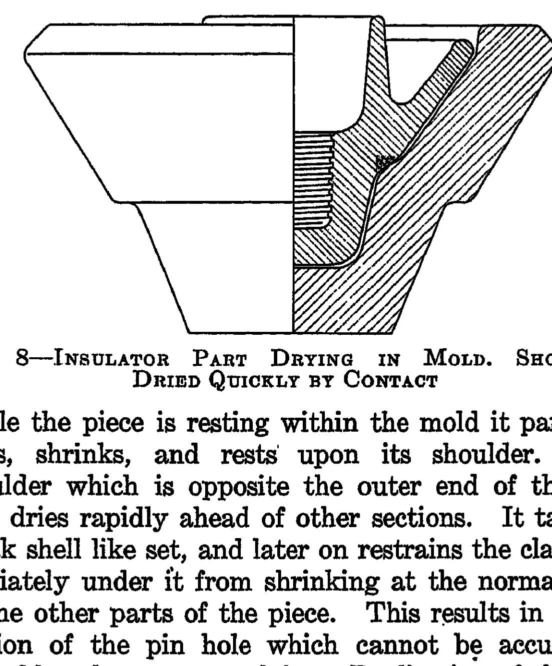

FIG. 8—INSULATOR PART DRYING IN MOLD. SHOULDER DRIED QUICKLY BY CONTACT

While the piece is resting within the mold it partially dries, shrinks, and rests upon its shoulder. This shoulder which is opposite the outer end of the pin hole dries rapidly ahead of other sections. It takes a quick shell like set, and later on restrains the clay immediately under it from shrinking at the normal rate of the other parts of the piece. This results in a distortion of the pin hole which cannot be accurately foretold and compensated for. Realization of this led to the adoption of the metal thread. This thread is now quite uniformly used in the pin type insulators of the higher voltages. Not only does it simplify construction and save time due to the exactness of its fit upon the pin, but in addition it is of special value in overcoming a hidden source of corona which might cause hidden stress and radio interference.

While we believe that the developments in insulator art have been worthy ones, we are by no means drifting into a self-satisfied condition. Organized research is constant and consistent and all indications are that insulators will not be the restraining factors in any future developments no matter how rapid those developments may come.

Discussion

S. Withington: The increasing reliability of insulators for medium and high voltages is a source of a great deal of gratification to all who are interested in maintaining the integrity of power supply, and there is no doubt that there has been satisfactory advance in this direction, as those associated with transmission and distribution of power before the war will agree. It is perhaps an overstatement, however, to say as Mr. Hawley does, that "insulators even of the largest size have established a perfect life record over a period of fifteen years."

It is true that the initial cost of insulators is relatively small when compared with the total construction expenses involved in a transmission line, and it is also true that this cost is relatively unimportant where continuity of service and the cost of replacement are considered. Nevertheless, the fact remains that the initial cost of standard types of porcelain insulators has risen in the past few years more than the normal indexes would seem to justify, and it is to be hoped that when the expenses of development to which Mr. Hawley briefly refers have been amortized there will be a marked decrease in cost of the consumer.

It would be of interest if Mr. Hawley were to expand his reference to the metal threaded hole for pin insulators. This is a development which is especially important in connection with the curing of cement at suitable temperatures to which Mr. Hawley refers.

Steam railroad electrification presents an important field in the use of insulators. In addition to the problems presented by the smoke from steam locomotives operating over electrified tracks, the requirements in general are similar to those of standard distribution and transmission lines, but the support, and particularly the dead-ending of the catenary system, produce somewhat heavier mechanical stresses and it is necessary that insulators be designed accordingly. There are numerous occasions also where on account of close clearance and for other reasons special forms of insulators are required. Pedestal type insulators are often necessary at low bridges, tunnels, etc., and the closest attention of the manufacturers should be given to satisfactorily adapting insulator design to these general requirements. It is probable that with increasing electrification of railroads more attention can be given to this phase of the subject and a satisfactory solution reached for the various problems involved.

A. O. Austin: The general characteristics of insulators having different types of mechanical construction are shown in Table I.

In the past losses due to abnormally high working loads have been negligible although losses due to differential thermal expansion or to concentrated loads have been very high, necessitating reinsulation in many cases.

Where long life and reliability are desired, low stress in the dielectric, due to the combined working load and differential expansion, is far more important than a good factor of safety for the working load based on the maximum or ultimate on test. Mr. Hawley has pointed out that the applied load produces an outward thrust tending to expand the cap, which may be regarded as the abutments in an arch structure.

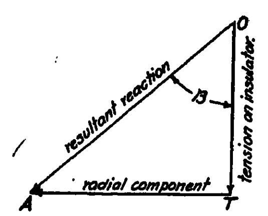

FIG. 1

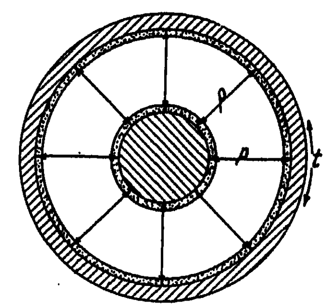

FIG. 2

Figs. 1 and 2 show the general relation of stresses produced by the working load.

Let $O\,T = L$ = load applied to insulator.

Then $O\,A$ = force in magnitude and direction, between the pin and bead or rim of cap, due to load $O\,T$.

$A\,T = P$ is the horizontal component of $O\,A$ or the total radial stress set up in cap and porcelain.

Then $P = L \tan \beta$

If D is cap diameter at bead or rim, $\pi\,D$ is the circumference and

$$p = \frac{P}{\pi\,D} = \frac{L \tan \beta}{\pi\,D}$$ = radial stress per inch of cap circumference.

TABLE I

Style	Construction	Characteristics for working loads			High test loads	Inherent limitations
		Light loads	Medium loads	Heavy loads		
1	Porcelain and metal fixed	Good	Fair	Heavy metal parts with high thermal stress	Fair	Low permissible temperature range and stress in metal
2	Compensated by slipping or wedging	Good if slipping does not take place due to thermal expansion of cap or contraction of pin	Good if slipping does not take place followed by reduction in load or temperature	Good for moderate range of temperature and load	Good	Shearing stresses due to variation in loads and temperature
3	Resilient metal and joint	Good	Good	Good	Fair	Cap and porcelain distortion
4	Restoring compensated	Good	Good	Good	Good	Shear due to small bearing area and concentrated load
5	Resilient and compensated	Good	Good	Good	Good	Cost
6	Link	Good	Fair	Poor	Poor	Shear due to small bearing area and to inherent form
7	Porcelain in tension	Good	Good	Good	Good	Necessity of multiple strings to offset mechanical hazard

If t = tangential stress in bead of cap

$$t = p\,r = \frac{p\ D}{2} = \frac{L \tan\beta\ D}{2\,\pi\ D} = \frac{L \tan\beta}{2\,\pi}$$

The circumferential stretch in the cap bead for load L will then be

$$\Delta\,C = \frac{t\,\pi\ D}{A\ E} = \frac{L \tan\beta}{2\,\pi} \cdot \frac{\pi\ D}{A\ E} = \frac{L \tan\beta\ D}{2\,A\ E}$$

Where A = cross sectional area of cap bead and
E = modulus of elasticity.

From this it will be seen that dividing by π gives the diametrical distortion $\Delta\,D$.

$$\text{Hence } \Delta\,D = \frac{L\ D \tan\beta}{2\,\pi\ A\ E}$$

By applying the proper values to the above equation and setting up a similar equation for the deformation of the porcelain, the radial distortion may be computed. If we assume that this amounts to approximately 0.008 in. for both cap and porcelain, and that the slope of the bearing ring of the cap $\angle\ Y\,O\,T$, is such that the tangent of $\angle\ Y\,O\,T = 0.5$, the amount of slip between the cement and the bearing surface of the cap which will compensate for the distortion, can be readily computed, or the

Longitudinal slip = 0.008/0.5 = 0.016 in.

While the slipping readily compensates for the distortion, giving high test values, reference to Fig. 3 shows that with the reduction of load a heavy unbalanced radial component may result which will tend to cause shearing of the porcelain. The coating of the surfaces with asphalt, graphite or metal foil will tend to control the coefficient of friction. The chief difficulty is that the coefficient of friction is likely to change with time.

While a few of the very high ultimate insulators were made some years ago in which the cap slipped to give the highest ultimates, it is believed that the initial stress set up by the temperature of assembly was such that slipping did not take place under maximum working load. The last of the above equations shows that the increase in diameter of the cap due to a given load will vary directly as the diameter and inversely as the effective cross section of the area and the modulus of elasticity. This has long been recognized, as many of the very heavy insulators used for long spans and catenary work have had reinforcing ribs to reduce cap distortion. Heavy cap construction, however, may result in high shearing stresses with low temperatures and light loads unless the pressure is tapered off near the edge of the cap. Reference to Fig. 3 shows the general relation of stress components for the insulator shown in Fig. 5 of Mr. Hawley's paper.

With a heavy plastic material such as asphalt, the angle L during setting up the load may be much smaller than the angle θ which is effective in restoring the porcelain and cap to normal condition. While this arrangement is beneficial in giving high test value, the shearing stress set up in the porcelain with light working loads may create a hazard. Since porcelain is relatively weak in tension and shear, unbalanced radial components which will set up shearing stresses are dangerous, regardless of the ultimate as they may cause "dough-nutting" which is due to the radial stress from the cap shearing the head of the insulator from the flange at low temperature or under a light load following a heavy load.

Fig. 2 of Mr. Hawley's paper is hardly applicable to insulator design as the large section of metal in the ring surrounding the pin reduces distortion to a negligible quantity. The very short cement strut between pin and ring will have but slight distortion compared to the very long strut made up of cement and porcelain in the insulator. Furthermore, a crack in the cement due to a displacement might not cause failure whereas a crack in the insulator due to distortion would result in dielectric failure with the possibility of mechanical failure due to an explosion from discharge through the fault.

In many of the earlier insulators equipped with sanded surfaces, the sanding was covered with glaze, the sand grains forming pyramids with the surface. At high mechanical loads there is a tendency for this surface to slip and compensate for distortion. It would seem that it is this slipping which increases the mechanical ultimate on test. This, however, is gained at the expense of resiliency in the joint.

The mechanical characteristics which may be developed in the porcelain depend to a large extent upon the method of making the test and the size of samples, the small samples giving abnormally high values which cannot be developed in the larger sections necessary in practical construction. A glaze which will tend to cause crazing will reduce the mechanical ultimate; whereas a glaze which will tend to cause shivering may increase the mechanical ultimate for some conditions. For best conditions, the linear coefficient of expansion of the glaze and body should be the same. It is believed that the latter condition will produce the best results as there are many insulators which have been in service for some years in which there is no evidence of failure. The first of the insulators of the type shown in Fig. 7 were installed in 1914 and have shown no evidence of cracking.

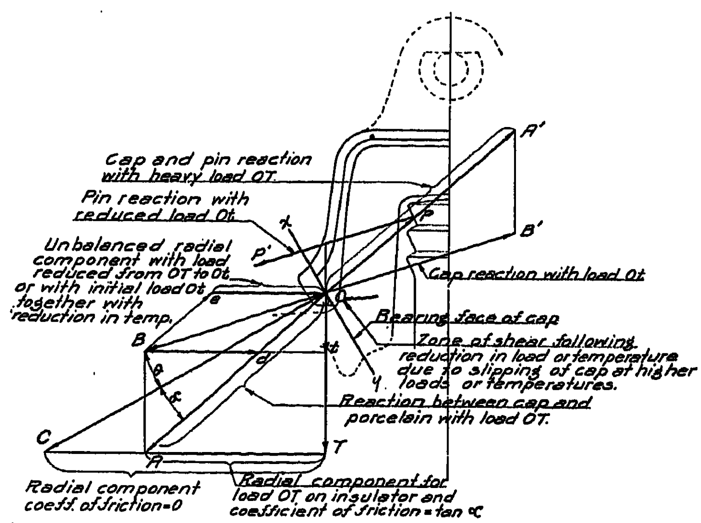

FIG. 3—DIAGRAM SHOWING CHANGE IN MAGNITUDE AND DIRECTION OF STRESSES IN INSULATOR WHERE DISTORTION IS COMPENSATED BY WEDGING AND SLIPPING

The limit of 267 deg. given by Mr. Hawley applies to porcelain only. Even in this case the figure must be materially reduced for concentrations of stress owing to the shape of the parts. Where porcelain and metal are used together the limits in temperature may be comparatively low. To offset this limitation the resilient joint is exceedingly valuable for either the pin type or suspension insulator.

If the conditions in Fig. 8 cause trouble, they can be largely remedied by coating the mold so as to prevent absorption of water at the shoulder, or by trimming the case hardened surface while the insulator part is soft.

If thin metal thimbles are used for threads there is always danger that the screwing of the insulator on the pin will produce a dangerous longitudinal or radial stress which will cause destruction of the insulator. It is, therefore, advisable to use heavy thimbles which will prevent damage to the insulator. With this arrangement, however, the insulator is subject to a thermal stress which is lacking in the case of the insulator having the thread made in the porcelain. The longest lived

insulators are apparently those which have threaded porcelain pin holes mounted on lead tipped pins, of proper design.

While the correction for distortion in the suspension insulator pointed out by Mr. Hawley is highly desirable for heavy loads, it is even more essential that the stress return to normal condition with the relief or the reduction of the load. Coatings which flow are not resilient and any unevenness in a coating with rigid parts adjacent may cause a concentration of stress and destruction. While a compensating or resilient structure for the cap or outer cement joint can be used to advantage, the cost of this type of construction is such that with the present high standard of insulators it has been impossible to commercialize the design embodying this feature. Reducing the coefficient of friction of the surface to zero will make the compensated type of construction safe over a much wider range of working conditions. It would seem, however, that this type of construction must be brought about by a roller bearing surface of joint or one equipped with tilting struts.

In the past, insulators having high ultimates have always shown the shortest life. It is, therefore, a serious mistake to use an insulator having a higher ultimate than is necessary for the maximum working load as the effective factor of safety for the maximum stress in the porcelain may be seriously lowered due to increased thermal stress from the stronger metal parts.

The time lag before defects are apparent, together with the wide variety of conditions encountered in service, makes it exceedingly difficult to predict results from design or accelerated tests.

K. A. Hawley: Mr. Withington's statement that the cost of insulators has risen more than the normal indexes would seem to justify is quite true, but it must be realized that the great improvement in the design and quality of high-voltage insulators which has occurred in the last decade has necessitated a great increase in overhead cost. The larger manufacturers maintain million-volt high-voltage laboratories which have a very large carrying capacity. The plant routine is much more extensive than ever before. For example, some years ago the routine electrical test applied to suspension insulators was simply a 60-cycle flash-over on the unassembled porcelains. Today the porcelains are flashed over at both 60 cycle and high frequency, assembled, pulled to 40 per cent of their guaranteed strength, and then flashed over again. The other routine processes of inspection and check throughout the plant have been extended in a manner similar to the electrical tests in order to produce units of the reliability which is now demanded.

Insulators are required to be nearly perfect, surface imperfections being no longer tolerated. This perfection has been reached only at a marked increase in cost which must necessarily be carried by the customer.

Mr. Austin's statement that the linear coefficient of expansion of the glaze and body must be the same does not check up with our test results. It is impossible to test a glaze and a body with respect to the coefficient of expansion separately and then to put them together and to expect thus to get the best results. The intimate contact between the porcelain and glaze causes some of the constituents of the glaze to run into the body and vice versa. We have definitely found that a glaze which will give the highest mechanical strength to a given porcelain will give the best results in insulators.

The use of metal thimbles in the pinholes of pin type insulators cannot possibly be more of a hazard to the insulator when screwing it on to the pin than would be the case with the ordinary plain pinhole and lead-covered pin. The thickness of cement between the thimble and the porcelain will go a long way towards distributing any stress which may be produced, and in preventing a concentration on the porcelain itself which might produce cracking.

It is impossible to agree with Mr. Austin's statement that insulators having high ultimate strength have always shown the shortest life. It is very true that an insulator may be designed which will give a very high ultimate strength and a low mechanical and electrical strength, but if the design is correct these two points will be very close together and it may be expected that such insulators will give a much longer life in service than those of low mechanical strength, other things being equal. The thousands upon thousands of high-strength insulators that have been giving perfect service for years substantiate this.

Due to the heavier line construction which is becoming more and more prevalent, insulator designs that will be the most effective from a mechanical standpoint will be the most economical from a cost standpoint. It is hard to reconcile Mr. Austin's statement regarding insulators of high ultimate strengths when it is realized that the units which are being made today by a large majority of the manufacturers have mechanical strengths practically 50 per cent greater than units of the same size which were made a few years ago. This increase in strength has been brought about by better attention to small details and a better understanding of ceramics. It is believed that the modern units will give service in the field of a character which has never been surpassed. It is only fair to give to the operating companies the economic advantages brought about by constant research work in the mechanical and electrical design of porcelain insulators.

Steam Power Development
of the Pacific Gas & Electric Company

BY RICHARD C. POWELL[1]
Associate, A. I. E. E.

Synopsis.—Improvements in steam power generation and economic changes in the fuel supply have caused increasing interest in steam power on the Pacific Coast.

After a brief history of the development of steam power on the system of the Pacific Gas & Electric Company, the author discusses some of the fundamental factors entering into the problem of providing additional steam plant capacity for this company in accord with the changed economic conditions.

The author describes recent work completed and under construction and gives some of the economic results obtained and expected.

INTRODUCTION

As a result of recent progress in the art of electric generation by steam power, most of the utilities on the Pacific Coast are either engaged on or planning power developments in which steam is predominant or occupies a very prominent position. Consequently, the economics and design of steam plants formerly of little interest to most Pacific Coast utility executives and engineers, are now of increasing importance.

In this paper will be discussed some of the fundamental factors entering into the problem of increasing the steam electric generating capacity on the system of the Pacific Gas & Electric Company and a brief description will be given of work recently completed and under construction. This will be preceded by a brief history of the steam power development of this company and a short description of the design features of the older plants together with service and operating requirements. This will serve as a background to the general picture and enable one readily to orient himself with respect to the various features involved.

HISTORY

The electric system of the Pacific Gas & Electric Company and its subsidiaries as it now stands, is essentially an interconnected system supplying service to almost the whole of Northern and Central California, an area roughly 425 miles long and 150 miles wide with a peak demand of about 850,000 kw. and an annual generation of about 4,500,000,000 kw-hr. Fig. 1 is a map of the generating and transmission system. Out of a total of 1,100,000 kw. in generating capacity, 300,000 kw. or roughly 30 per cent is in steam. It has reached its present size by consolidation and extension covering a period of over 40 years. The nuclei for this growth were the independent systems which had been started in San Francisco, Oakland, Sacramento, and San Jose, all supplied from generators driven by steam engines. Thus, originally the output was entirely steam power.

The development of high-voltage transmission about 1900 enabled water power to be brought to these and other cities at a cost much lower than steam power, which was then unable to hold its position and was rapidly shoved into the background. Steam power would undoubtedly have been almost entirely supplanted but for two factors, *viz.*, first, the unreliability of those early lines, and, second, the entire lack of sites for, or prohibitive cost of reservoirs to provide the

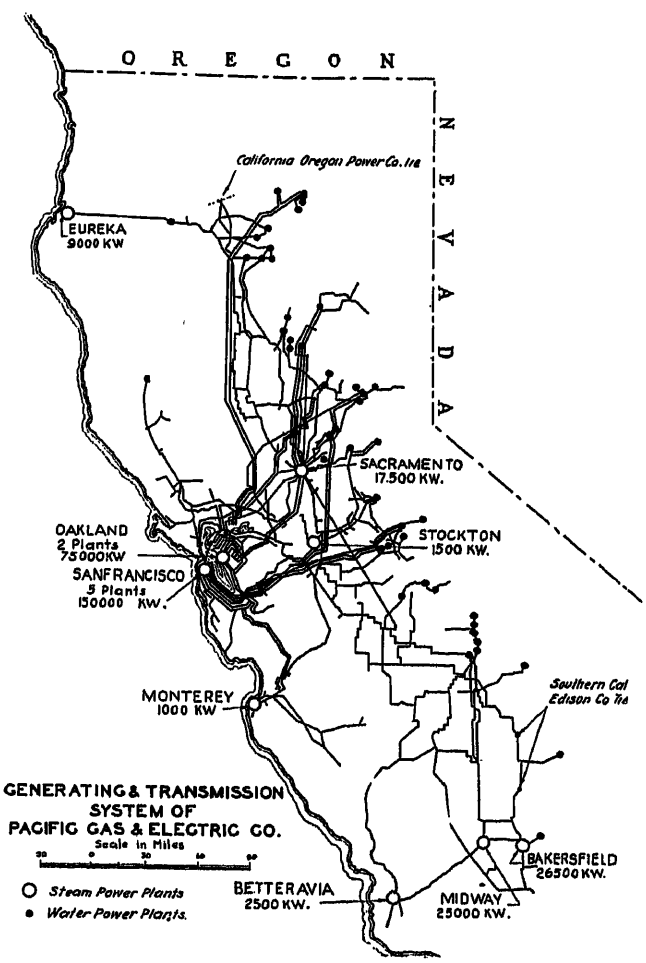

FIG. 1

necessary storage to enable the water power plants to carry the load during the dry seasons when the stream flows fell greatly below normal.

During this period of great water power development supplementary steam power was necessary, and hence the growth of steam and water power followed somewhat roughly together. Up until about 1924 the ratio

1. Pacific Gas & Electric Co., San Francisco, Calif.

Presented at the Pacific Coast Convention of the A. I. E. E., Portland, Oregon, Sept. 2-5, 1930.

30-147

of total steam plant capacity to system peak demand for the Pacific Gas & Electric Company system varied rather consistently from about 40 to 60 per cent and the ratio of kw-hr. generated by steam to the total, ranged from about 15 to 30 per cent. For the years 1924 to 1929 inclusive, these data are shown by the curves in Fig. 2. During these years the ratio for kw-hr. output swung through a very wide range, the high point being slightly higher and the low very much lower than for any previous year. The high point of steam generation was for the excessively dry year of 1924 and the low point was in 1927 when there was an excess of water power due to the completion of several water power projects in Northern California.

The increase in steam power capacity was obtained by the gradual process of adding one unit at a time,

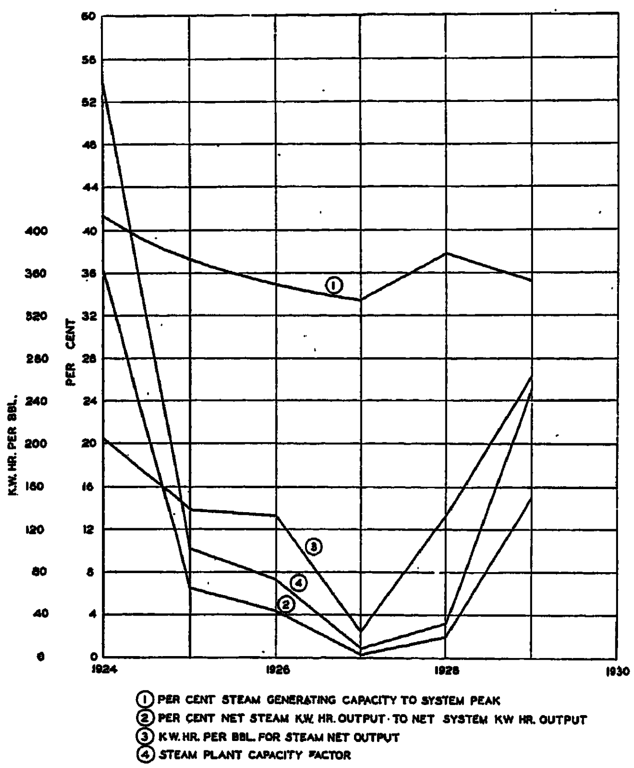

Fig. 2

first engine driven up until 1907 when the first turbine, a vertical one of 9,000 kw., was installed at Station "C," Oakland. The engines were then within a few years all replaced by turbines with the exception of two 3,500-kw. units at Station "A," San Francisco, which were just recently removed to make room for a 50,000-kw. turbine set. At the beginning of 1928, there were seven steam plants on the system ranging in capacity from 1,000 to 64,000 kw. The largest turbine unit was 15,000 kw., the largest boiler 8,900 sq. ft., and the highest steam pressure and temperature were 250 lb. and 540 deg. fahr. respectively.

The requirements for the steam plants during the period under review were: (1) low investment cost since the load factor on steam over a period of years was not high, (2) high reliability, since steam was always the pinch hitter during seasons of low water and at times of sudden failure of a line, flume, or some other part of the water power and transmission system, and (3) the ability to pick up full load quickly from a very light load condition. On the whole, these plants met the above requirements very satisfactorily. They have never seriously failed to meet the service demands made upon them in the way of picking up load in the event of line or other failures on the water power system although no especial features of design were employed to enable the equipment to respond rapidly to a sudden increase of load. Dependence was placed entirely upon keeping sufficient turbine capacity on the line at very light load, that is, from just floating to 5 per cent of rating, with corresponding boiler capacity either steaming or with pressure at or near that of the line, and the ability with oil firing to get boilers to full steaming capacity in a very short time. Experience has proved that under the conditions just outlined, full load could be picked up with little or no disturbance to service. Usually the disturbance was for only the momentary time required for the operator to separate the load to be protected together with its steam standby from the transmission system in trouble.

The efficiency of these plants was rather low, averaging about 30,000 B. t. u. per kw-hr. and the operating and maintenance costs were rather high during dry years when the plants were forced for considerable lengths of time, but since the excessively dry years occurred on an average of only one in seven, the average maintenance costs over a seven year cycle were not excessive for plants of their time.

At the beginning of 1928, the investment per kw. varied among the plants from about $60 to $80; the steam pressures and temperatures were low, the design was simple with no economizers, fans, or automatic devices worth mentioning. The auxiliaries were mixed steam and electric in order to maintain a sort of heat balance at or near full load and to draw most or all of the power for auxiliaries from the water power system during light load times when there was an excess of water.

Plans for Steam Power Development

About four years ago it became apparent that the economic relation between steam and water power had become reversed. The reasons for this change were:

1. The generally increasing cost of additional water power due to the best sites having been developed and, for sites already developed, the rather prolonged series of years of subnormal water supply which indicated that the supply was not so great as formerly supposed.

2. The rather pronounced lowering of steam power costs, due to improved efficiency, lowering investment, operating, and maintenance costs, and for California, at least, the oversupply of oil with consequent reduction in price, and finally the tremendous production of natural gas and its supply to Northern California.

A comprehensive plan was developed which would provide not only for the immediate needs, but also for at least fifteen years hence in the matter of the acquisition of steam plant sites and transmission line rights-of-way for lines necessary to connect such sites with the general system. The main objective involving power development is, of course, always the economic one to provide power at the lowest possible cost. Furthermore, for the Pacific Gas & Electric Company, the new units should perform at least as well as the existing ones in the ability to pick up load quickly. In working up this plan consideration was given to all the elements involved which included:

1. Sizes of units and when and where to be installed.
2. Costs for investment, maintenance, operation, and fuel.
3. Obsolescence.
4. Operating reliability and flexibility.

A careful study was made of all the factors entering into the above elements. These factors included such items as:

1. New plants *versus* rebuilding of the old plants.
2. Sizes of turbine and boiler units.
3. Steam pressure and temperature.
4. Extraction heaters, economizers, air heaters, and furnace water walls.

Most, if not all large systems have a need for two types of generating units, the first highly efficient for so-called base load operation, and the second for peak load service and reserve. The Pacific Gas & Electric Company also requires a third type which is required only in excessively dry years, the occurrence of which are infrequent and uncertain. That any given year will be very dry is not known until about February. It is very difficult if not impossible to provide against such deficiency of water, unless such abnormal deficiencies are recognized as liable to occur and provided for at all times. Examples of where failure to provide for this contingency have resulted in power shortage are well known. On the Pacific Coast such cases occurred in California in 1924 and in the Northwest in 1929. The Pacific Gas & Electric Company has never found it necessary to cut off load on account of a dry year except during the war when it was required to curtail new construction on account of war conditions.

On account of the available space conditions at Station "C" and the nearer location of Oakland to the water power supply, it was determined that increased capacity at Station "C," at least to the extent of 75,000 kw. would conform to the second type of plant just mentioned and that Station "A" would provide the first type. To provide for the third type of capacity, it was decided to retain the North Beach plant in San Francisco and the Station "B" plant in Sacramento with a combined capacity of 35,000 kw., and these during normal years would probably be shut down.

The problem of how best to provide peak and reserve capacity is not always clear as is evidenced by the discussions which appear from time to time, and include proposals such as steam plants with accumulators and pumped storage for water plants. It is believed that the most practicable way to obtain such capacity in steam is to provide overload capacity for each unit. The rating of both turbines and boilers is entirely arbitrary. The maximum output of a turbine is determined by the maximum steam flow for a unit built to a given frame. A boiler can be forced to a very high output. The ratings may be set according to the efficiencies desired for both turbines and boilers and the maintenance cost for boilers which will increase at high outputs.

Cost studies showed that it would be more economical to rebuild and enlarge Station "A" in San Francisco and Station "C" in Oakland than to provide the same additional capacity at new sites. Both of these sites are admirably located with respect to both cooling water and their loads, and for both plants there are substantial investments in electrical equipment and outgoing duct lines and cables which can be utilized for greater capacity. The Station "A" site is suitable for a total of about 260,000 kw. and that at Station "C" for about 175,000 to 200,000 kw. It was therefore decided that the program would proceed along the line of first developing the Station "A" and Station "C" sites.

It is, of course, always the desire to hold investment costs as low as possible, but this should not be carried to the point where maintenance and operating costs are adversely affected. It was fixed as a policy, however, that no investment cost would be increased to reduce any estimated maintenance or operating costs unless such reductions were sufficiently large to appear certain of occurring.

The size of turbine and boiler units has a marked effect upon costs. This is particularly true of large boiler units. Investment per kw. is lower for large units, efficiencies are higher, and operating costs are much lower, and the investment for automatic control and instruments is decidedly lower. Large units, especially boiler units, are more flexible as regards load fluctuations and there is no reason to believe that they are not just as reliable as small units. Costs for maintenance and periodic inspection are less for large turbine units than for small ones and should be no higher for large boiler units, and maintenance costs for automatic control equipment is much less, since the cost and amount of such equipment is almost entirely dependent upon the number of units and not upon the size.

In the matter of pressure and temperature, it was recognized that the trend was very definitely to higher pressures and temperatures. Careful estimates made in 1926 showed that a plant operating at 450 lb. pressure should cost no more than one operating at 250 lb. although the use of 650 lb. with reheating would cost more. No very careful estimates at that time were made for 1250 lb. since that pressure was then regarded as still in the development stage. The use of pressures

and temperatures as high as consistent with reliable operation will, of course, have a favorable influence upon obsolescence.

Extraction heaters, economizers, and air heaters, although adding complication as compared with the old plants did not seem to affect reliability adversely and their use was considered entirely a matter of economics. With reference to furnace water walls, an installation made in 1925 in one boiler as a trial had definitely showed that their use would not only reduce furnace maintenance, one of the largest items of boiler room maintenance, but would greatly improve reliability. They were necessary if boilers were to be operated at high rating with mechanical atomizing oil burners, since with such burners furnace temperatures of the order of 3200 deg. fahr. are encountered.

To obtain increased steam power capacity, the first in-installation was to be made at Station "C," to be followed with the next increase at Station "A," San Francisco. From the studies made in 1926, it was concluded that design for Station "C" should be based upon 450-lb. drum pressure, approximately 750 deg. fahr. total steam temperature, large boilers with water walls, the question of extraction heaters, economizers, and air heaters to be a matter of economics and layout in the space available. It was further concluded to install automatic control.

Installation at Station "C," Oakland

The installation for a 37,500-kw. unit at Station "C" was started in 1927 and put into operation in October, 1928. The size of turbine was determined by the then existing turbine room which permitted with a small extension the erection of two 37,500-kw. turbines in the space occupied by two vertical units, one a 9,000 kw. and the other a 12,000 kw. In line with the type of capacity desired, *viz.*, the second type mentioned above, and on account of space limitations, a 37,500-kw., 9-stage impulse multi-valve turbine with guaranteed overload capacity of 42,000 kw. was selected. This was quite a departure from established practise. As compared with the conventional unit of this size, it has better efficiency up to about 30,000 kw. and by extracting heavily its efficiency is not greatly less for higher loads, and the cost for the unit, foundation, and building was about $1.50 per kw. less. For the load conditions it will have to meet during its life, it should be considerably more efficient.

Straight tube sectional header boilers were decided upon because experience on the whole had been better with this type than with the bent tube type. The size was selected by making the width the maximum that could be obtained for a riveted drum, and the number of tubes high was made such that without an economizer, the preheated air temperature would not exceed 500 deg. fahr. With 24-ft. tubes, this resulted in a very economical unit of 35,453 sq. ft. with a maximum guaranteed output of 425,000 lb. per hr. having about 84 per cent efficiency at maximum output with an air heater of 51,232 sq. ft. Two such units were installed, one to serve as a spare for the first and future turbines. A maximum steam temperature of 730 deg. fahr. was selected as the highest then considered desirable without the use of alloy tubes.

Approximately 25 per cent of the throttle flow is extracted for feed water heating with a final temperature of 390 deg. fahr. A single pass condenser of 28,000 sq. ft. was installed and although the capacity of the plant was increased from 33,500 kw. to 68,000 kw., no additional pump capacity for circulating water was required.

Automatic equipment was provided for combustion control, condenser hotwell level, feed water pressure, and drum water level.

Auxiliary power is supplied from two three-phase transformers connected to the main station buses. Most of the motors, including one 500-hp. synchronous motor, are started on full voltage.

This brief description will give an idea of the type of design and character of the equipment. The over-all cost of the plant including land, building, etc., after the installation of this unit and increase to 68,000 kw. capacity was very closely the same per kw. as for the original 33,500-kw. plant, although the efficiency was about doubled and the operating and maintenance costs reduced to about half on a kw. basis. The turbine has a maximum output of 43,750 kw. and each boiler has put out 435,000 lb. per hr. The boiler room installation is quite compact and occupies 7.7 sq. ft. of ground area and 586 cu. ft. of building volume per 1,000 lb. per hr. output. This includes the boilers, air heaters, fans, and fuel oil pumps and heaters.

The new unit was put into service in October 1928 and shortly thereafter on account of very cold weather in the mountains with consequent reduction of water supply, was required to carry practically a continuous load of 43,750 kw. until some time in February. It was therefore not until the spring of 1929 that the turbine or a boiler could be taken out of service for the necessary adjustments of automatics, etc., incident to the starting up of a new unit. Leaving out of account the time when equipment could have been operated, but was out for adjustment of automatic equipment, the turbine during 1928 was available over 99 per cent of the year and both boilers about 96 per cent. The turbine output was on a 65 per cent capacity factor and the net output was just at the rate of 14,000 B. t. u. per kw-hr. The auxiliary power was 3 per cent. It is to be noted that the unit was loaded very unfavorably since for practically all of the time the load was either very light (500 to 1000 kw.) or with heavy overload at 43,750 kw. and for very little or none of the time at the most efficient point of about 30,000 kw.

Curve 3, Fig. 2, shows the average kw-hr. per bbl. of oil for all the plants for the years 1924 to 1929 inclusive. The effect of the Station "C" installation is easily seen

by referring to curve 4. In 1924 operating on 54 per cent capacity factor for the total system steam capacity, the net output was at the rate of 205 kw-hr. per bbl., but in 1929 although the capacity factor was only 25 per cent, the net kw-hr. per bbl. was raised to 260. Had the capacity factor been 54 per cent, the kw-hr. per bbl. would have been about 280, which represents a saving of 36 per cent in fuel.

Installation at Station "A," San Francisco

In 1928 studies were made for the rebuilding of Station "A" and included plans and estimates for 450, 750, and 1350 lb. drum pressures. The use of any pressure between 450 and 1350 lb. was shown to be uneconomical and it appeared that 1350 lb. might cost $3.00 per kw. more than 450 lb. However, there was a very pronounced trend toward lowering costs for 1350 lb. equipment and an increase in the size of boilers which manufacturers were willing to build. All items considered, it was decided that the use of 1250 lb. throttle pressure and 750 deg. fahr. total temperature would be the most economical and that the plant could be rebuilt for 1350 lb. cheaper than for some lower pressure. Even at some higher cost for the equipment, the ultimate plant would be cheaper per kw. because, first, more capacity could be installed in the existing buildings, and second, the circulating water system required rebuilding and with the much less quantity of water needed this item was much less for the 1,350 lb. It was believed that the cost of 1,350-lb. equipment would go down as production increased, and that within a few years it would be possible to build a plant for this pressure as cheap as for some lower pressure. This view has proved correct for it is now definitely known that the costs for 1350 lb. are no greater than for 450 lb.

The old building space permits of the installation of 4 turbine units, each of about 60,000 kw. output, and 6 boiler units, each of 500,000 lb. per hr. maximum output. The installation now under construction consists of 2 turbine and 3 boiler units. The turbine units are each compound rated at 50,000 kw. with maximum output of 65,000 kw. at unity power factor. At a sacrifice of 10 B. t. u. per kw-hr. chargeable to the turbine room at the most efficient load point the maximum turbine output for the same frame was increased from 58,000 kw. to 65,000 kw. That is, for slight dedecrease in efficiency, considerable overload capacity was obtained. The arrangement of high- and low-pressure turbines is the so-called vertical compound with the high-pressure turbine and generator mounted on the low-pressure generator. This arrangement saves space and cost of foundations and simplifies somewhat the generator air cooler arrangement and the piping for cooling water.

The exhaust from the high-pressure element of each unit is reheated to 750 deg. fahr. before passing to the low-pressure element, first in a live steam reheater, the heating steam being saturated steam at 1,350 lb. pressure, and, second, in a convection reheater which is a part of the boiler unit.

By this combination of reheaters the temperature of the reheated steam is maintained approximately constant over a wide load range.

All of the steam for a turbine unit is reheated in a single boiler with no cross-connections on reheaters so that if a reheat boiler unit is out of service, the low pressure turbine will be run without reheat. Thus, two of the boilers now being installed are reheat boilers and the third is a so-called standard unit, that is, without reheat. The standard boiler provides some spare capacity and also the additional steam required for each turbine unit at loads when more than 500,000 lb. per hr. is required. The complication of piping for a reheat cycle is not so great as commonly assumed, particularly when all the reheating for a turbine unit is done in a single boiler, and is offset to a considerable extent by the fact that much smaller pipe sizes are required for 1250 lb. than for say 400 lb.

For the type of boiler unit which has been used in most of the 1250-lb. plants, the cost on a kw. basis is very little more than for a 400-lb. plant. Although the so-called boiler part, that is, drum, headers, and tubes, is costly, it is relatively small and most of the complete boiler unit surface is in other elements, that is, superheater, resuperheater, economizer, and air heater. Table I gives the percentages for the various surfaces.

TABLE I

	Per cent of heating surface			
	Reheat boilers		Standard boiler	
	Steam and water absorbing surface	Steam, water, and air absorbing surface	Steam and water absorbing surface	Steam, water, and air absorbing surface
Boiler	24.1	11.2	26.5	12.3
Water walls	3.6	1.7	4.0	1.9
Superheater	14.2	6.6	17.6	8.2
Reheater	18.0	8.3		
Economizer	40.1	18.5	51.9	24.0
Air heater		53.7		53.6

The Station "A" boilers have forged steel drums 52 ft. long, 5 ft. outside diameter with 4 in. walls and weigh about 70 tons each. The tubes are arranged 62 wide and 8 high.

The area and space occupied by the boiler and fan rooms are per 1000 lb. per hr. output, 9.35 sq. ft. and 865 cu. ft. respectively. In comparison with similar figures for Station "C" on a kw. basis, the area for Station "A" is 90 per cent and the volume 1.09 per cent of those for Station "C." At Station "A" the space is that of an existing building with height increased to provide for the fans and the cubic space could be reduced for a new plant. It appears that on the whole a high-pressure plant will require at least no greater space than a plant for lower pressure.

The remainder of the equipment such as fans, feed

water heaters, pumps, etc., are similar to that for lower pressure plants and requires no detailed description here.

The reconstruction of Station "A" is an example of the recent progress in the art of generating electricity by steam power, and shows how the great improvement in fuel economy has been effected without increase in capital. In fact for Station "A" there will be a marked reduction in investment. With the completion of the present construction, the capacity will have been increased from 64,000 kw. to about 160,000 kw., and it is expected that the over-all investment per kw. will be reduced by about $15.00 per kw. and the fuel, operating and maintenace costs per kw. reduced to one-half. With the completion to the ultimate capacity of about 260,000 kw. a further reduction of $5.00 per kw. is expected or a total of $20.00 per kw. The cost of the new Station "A" will be comparable with steam plant costs in Great Britain and Europe. The fuel consumption for the 1,250-lb. units should be at the rate per net kw-hr. of 12,000 B. t. u. or better.

Since plants for operation at 1,250-lb. pressure cost no more than for some lower pressure, undoubtedly in the near future there will be a number of plants at this pressure in operation on the Pacific Coast. Higher pressures and temperatures are to be expected in time, but with the present fuel situation, particularly in California, it is not anticipated that pressures higher than 1250 lb. and temperatures above 800 to 850 deg. fahr. will prove profitable for some years.

Summary

The author has outlined the development of steam power in the system of the Pacific Gas & Electric Company and attempted to discuss briefly those factors which are of most importance in the economical design of steam plants with especial reference to Pacific Coast conditions.

Grounding Banks of Transformers with Neutral Impedances
and the Resultant Transient Conditions in the Windings

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Synopsis.—*The question of grounding transformer bank neutrals through different impedances has recently arisen due to the desire to limit system single-phase and two-phase short-circuit currents. This limitation has been required to ease the duty on circuit breakers and assist in maintaining system stability. The use of resistance, inductance, and various combinations has been studied as to the effect on the short-circuit current and particularly upon lightning transients within the transformer windings and at the neutral. It was found that the use of resistance only may be undesirable on account of the high voltage at the neutral in limiting the short-circuit current. The use of inductance only may result in high voltages within the transformer and at the neutral due to lightning transients, which necessitates that the transformer be fully insulated throughout. Methods using parallel paths with the inductance, these parallel paths being designed primarily to reduce the lightning transients at the neutral, have been studied and found to limit the transients within the transformers to values approximating those for solidly grounded neutral which permit the grading of the transformer insulation. The method to be selected depends upon the individual case, but generally the use of the valve type lightning arrester is the simplest to apply.*

* * * * *

I. INTRODUCTION

MODERN methods of power transmission involve the transformation of energy with large high-voltage transformers, which usually have one or more windings connected in star and until recently solidly grounded at the neutral. With the increase in size of transformers and generating equipment, trouble has developed due to excessive currents under single- and two-phase short circuits. To relieve these conditions and to improve the stability of the system generally, the practise of inserting impedance between the neutral and ground of some of the transformer banks has been adopted.

Either a resistance or an inductance can be used for the impedance. Its purpose is primarily to limit the short-circuit neutral current. Having a knowledge of the circuits involved, the necessary impedance can be determined to limit the current to a safe value. With impedance in the neutral, the stresses within the transformer winding when subjected to lightning surges require similar study to that made for transformers with solidly grounded neutral. This is particularly the case since the impedance is selected with no thought of its performance under impulse voltages but only its performance under normal frequency short-circuit conditions. It is the purpose of this paper to study the characteristics of neutral impedances under lightning surge conditions and suggest means for improving their performance.

II. FACTORS INFLUENCING THE LIGHTNING TRANSIENT

The effect of voltage surges on transformers with solidly grounded neutral has been previously described.[1] The general factors influencing the transient phenomena are well known, but a brief résumé will be given here.

It was shown in the paper mentioned that the worst stresses within the transformer windings were those due to steep front short waves and steep front long waves. The former imposes the greatest stress upon the winding near the entrance terminal by virtue of its greater magnitude. With a short wave the stresses are proportional to the distribution of voltage determined by the capacitance relationship of the winding. This has been referred to as the initial distribution. With steep front long waves the initial distribution is essentially the same except for absolute magnitude, but the amplitude of voltage at internal points is greater due to oscillations within the winding. The magnitude of lightning voltages which can be propagated on transmission lines is limited by the line insulation and is lower for long than for short waves. A survey of laboratory and field tests on transmission lines and transmission line insulation gives a good indication of the characteristics of lightning waves expected in service. The curve, Fig. 1, estimated on the basis of some of these data, illustrates the variations in the maximum voltage expected on normally insulated lines with length of the traveling wave. Oscillographic records of lightning waves taken in the field, indicate that the greatest duration of voltage probably would not exceed 60 microseconds to one-half value, and the most rapid rate of rise was of the order of one microsecond to maximum value.

Waves having the characteristics of the two above would impose the most severe stresses upon trans-

*Both of the Westinghouse Elec. & Mfg. Co., Sharon, Pa.

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1. For references see bibliography.

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formers grounded through neutral impedance. It has been previously pointed out[2] that for short surges only a small amount of energy penetrates the winding as far as the neutral and consequently the increase in voltage at the grounding impedance will be very small. From the standpoint of stress at the neutral impedance and the interior of the transformer winding, it will be necessary to consider only the 60-microsecond surge. Therefore,

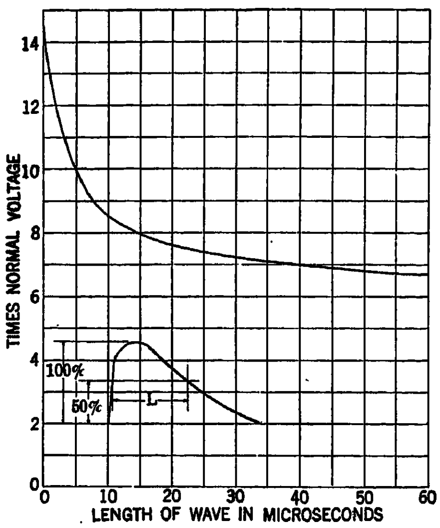

FIG. 1—VARIATION IN AMPLITUDE WITH LENGTH OF LIGHTNING SURGES ON NORMALLY INSULATED TRANSMISSION LINES

in performing the tests described below a wave rising to maximum in approximately one microsecond and of 60 microseconds duration to half value was used.

Another important factor influencing the amplitude of voltage in the transformers and at the neutral is the magnitude of voltage occurring simultaneously on the three separate phases. A traveling wave on one line induces waves of the same polarity in the other two lines, but the induced waves are usually of lower amplitude, depending upon the space configuration of the lines.[3] If simultaneous waves of equal amplitude are impressed on each of the three phases, the voltage at the

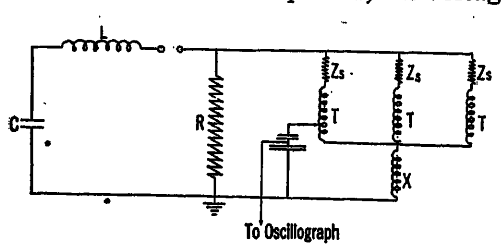

FIG. 2—SCHEMATIC DIAGRAM OF TESTING CIRCUIT

neutral would rise to three times the amplitude that it would if the wave was impressed upon one phase only. In making this investigation the worst condition of three equal surges is assumed.

III. TEST CIRCUITS AND METHOD OF TESTING

Impulses were generated by discharging banks of condensers through a resistance and impressing the voltage drop upon the transformer terminals. The windings of the transformers under test were connected together at the neutral and grounded through the impedance under consideration. The connections from the surge generator to the high-voltage terminals of these windings were made as short as practicable and terminated in lumped surge impedances of approximately 450 ohms. The remaining windings of the transformers were connected to ground through similar surge impedances. Fig. 2.

A surge was impressed upon the transformers and the potential at various points in the winding and across the neutral impedance was measured. The maximum value of the voltage was determined by means of a sphere spark-gap and the voltage-time relation recorded for at least one complete cycle with a cathode ray oscillograph. A capacitance potentiometer was used to reduce the voltage for measurement with the oscillo-

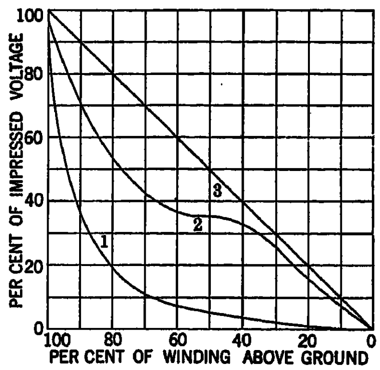

FIG. 3—VOLTAGE-TO-GROUND PRODUCED IN A TRANSFORMER WINDING WITH NEUTRAL SOLIDLY GROUNDED BY A 60-MICROSECOND SURGE

1. Initial voltage distribution
2. Maximum voltage by oscillation
3. Final or steady state distribution

graph. This potentiometer was of very low capacitance so that the constants of the circuit were affected very little.

The transformers used in making this study were 25,000-kv-a., 220-kv. power transformers of shell type construction, and of recent design.

The neutral reactors were air core and the neutral resistors were practically non-inductive.

IV. TRANSFORMERS WITH SOLIDLY GROUNDED NEUTRAL

To form a basis for comparing the effects of various neutral devices, the reaction of the transformers with the neutral solidly grounded was determined. The transient conditions involved in this problem have been analyzed elsewhere[1] and will not be considered here.

The initial distribution of voltage with the steep front wave is shown as curve 1, Fig. 3. The maximum voltage to ground occurring at internal points in the winding by oscillation is represented by curve 2 of the same figure. These two boundary curves define the envelope of oscillation of the internal voltage transient.

It is to be noted that the maximum voltage does not exceed the uniform distribution curve.

V. Transformer with Neutral Insulated

The initial distribution, Fig. 4, is practically the same irrespective of whether the transformer is solidly grounded, grounded through an impedance, or completely isolated. This is expected from the initial distribution curve of Fig. 3 which shows that but a small percentage of the voltage exists in the portion of the winding near the neutral. Consequently in considering the transient effect with various neutral devices the same initial conditions hold within practical limits.

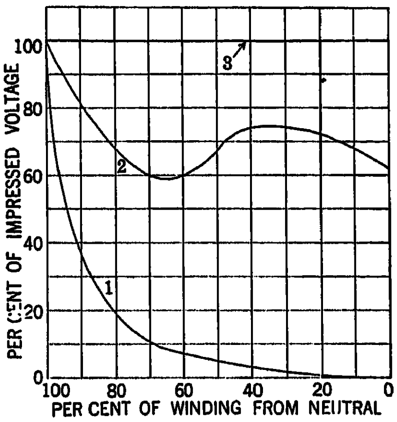

Fig. 4—Voltage to Ground in a Transformer Winding with Isolated Neutral

1. Initial voltage distribution
2. Maximum voltage by oscillation
3. Final distribution or axis of oscillation

The final distribution is quite different from that with the neutral grounded. When the neutral is isolated and a surge is impressed, the winding tends to assume the same potential throughout. In reaching this potential, it oscillates about the potential on the line terminal. The amplitude of the oscillation at the neutral depends upon the magnitude of the terminal voltage and the relation of the length of the surge to the natural period of oscillation. Under lightning surges the voltage rises to relatively high values. In the experimental case, the maximum amplitude in per cent of the impressed voltages are given in curve 2, Fig. 4.

It is to be noted that the voltage does not attain values in excess of the applied voltage. This is explained, as mentioned above, by the fact that curve 3 representing the initial axis of oscillation decreases as the voltage on the transformer decreases. Since the rate of decrease of the latter is rapid compared to the period of oscillation of the transformer, the oscillations do not develop to the extent that they would if limited only by inherent damping, as would be the case with an infinitely long wave.

VI. Transformer with Neutral Grounded through Resistance

When the transformer neutral is grounded through a non-inductive resistance, the axis about which the winding tends to oscillate is a straight line extending from the line to the neutral end of the winding. The voltage at the neutral will be raised to a value depending upon the value of neutral resistance, the relative effective impedance of the transformer winding, and the length of the traveling wave. In the limiting cases of zero resistance and infinite resistance, the axes coincide with those for a solidly grounded transformer and for an isolated neutral transformer, curves 3, Figs. 3 and 4. For finite resistances the axis lies between these limits.

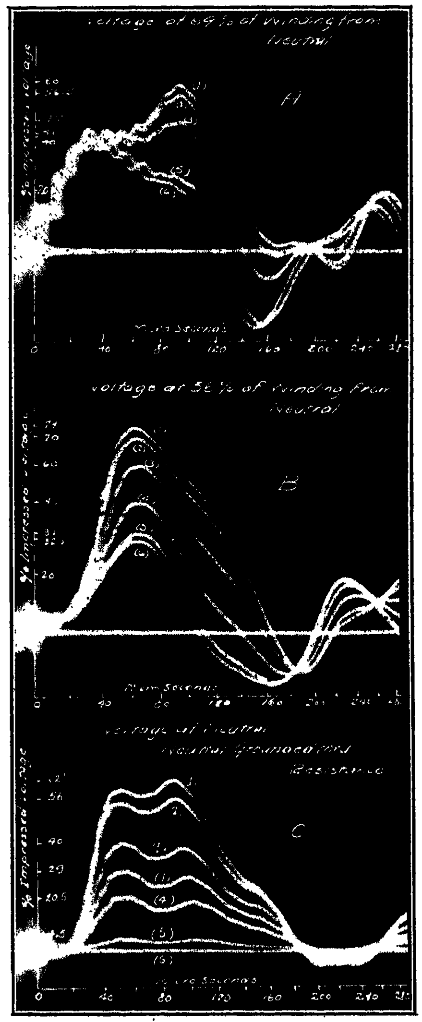

Fig. 5—Oscillograms Showing the Variation of Internal Oscillations in Transformer Windings with Different Values of Neutral Resistance

A—69 per cent of winding from neutral
B—36 per cent of winding from neutral
C—Neutral
1 – R = infinite (neutral isolated)
2 – R = 100,000 ohms
3 – R = 25,000 ohms
4 – R = 5,000 ohms
5 – R = 450 ohms
6 – R = 0 (neutral solidly grounded)

When the transformers are subjected to a lightning surge, the voltage at the neutral and the voltage throughout the winding rises to a value in excess of that

attained when the neutral is solidly grounded, depending upon the value of the neutral resistance and the characteristics of the applied surge. With the 60-microsecond test wave, the voltage at the neutral and at points in the winding 36 per cent and 69 per cent from the neutral are shown in the oscillograms, Fig. 5, for various values of resistance between the two limiting conditions. The axis of oscillation rises and the magni-

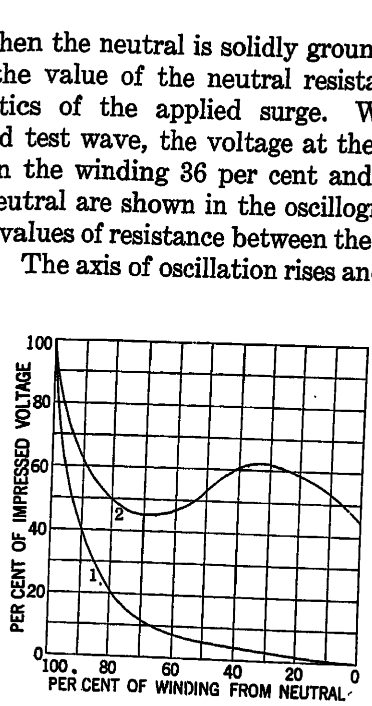

FIG. 6—VOLTAGE-TO-GROUND IN 25,000-KV-A. 220-KV. SHELL TYPE TRANSFORMER WINDINGS WITH NEUTRAL GROUNDED THROUGH A 315-MILLIHENRY REACTOR

1. Initial distribution of voltage
2. Maximum voltage by oscillation

tude of voltage increases with increasing resistance. With the transformers grounded through 450 ohms resistance, the rise in voltage at the neutral was approximately 4.5 per cent. The increase in voltage at the two points in the winding, mentioned above, over that for a solidly grounded neutral was small, only about 2 to 3 per cent. With larger values of grounding resistance, the increase in voltage becomes more pronounced, particularly in the portion of the winding near the neutral.

VII. TRANSFORMER NEUTRAL GROUNDED THROUGH INDUCTANCE

In the case of the neutral grounded through inductance as in the previous cases, the initial distribution is the same as for solidly grounded neutral. The oscillatory voltage occurring across the reactor is a function of the relative inductance of the transformer and reactor, and the relative length of the traveling wave. The higher the ratio of reactor inductance to transformer inductance, the greater will be the rise of voltage at the neutral. During the transient existing in the transformer winding, the reactor enters into oscillation with the transformer winding. This results in an increase in voltage stress at the neutral and throughout the winding. This is illustrated in the curves of Fig. 6 and Fig. 8. In the case illustrated, the bank of 25,000-kv-a. transformers was grounded through a reactor of 315 millihenrys inductance. The self inductance of the transformer winding was calculated to be 850 millihenrys. The reactor was designed so that the dynamic rise of voltage was approximately one-half normal line voltage, and the kv-a. capacity as compared to that of one transformer was 144 per cent.

A reactor is a desirable means for grounding the neutral, since its reactive drop adds directly to the impedance voltage of the transformer, reduces the shock of short circuit on generating equipment, has less watts loss, and can generally be designed more economically than a resistor. A method of reducing the excessive transient voltage at the neutral is, therefore, highly desirable. Several ways of improving this feature have been proposed. Some of these are described below.

A. Reactor Shunted with Resistance. If the neutral reactor is shunted by resistance, a part of the energy is conducted directly to ground and a damping effect imposed upon the oscillations in the reactor circuit. The voltage at the reactor will be reduced by an amount proportional to the energy by-passed. Obviously the lower the resistance used the lower will be the voltage across the reactor. This, however, cannot economi-

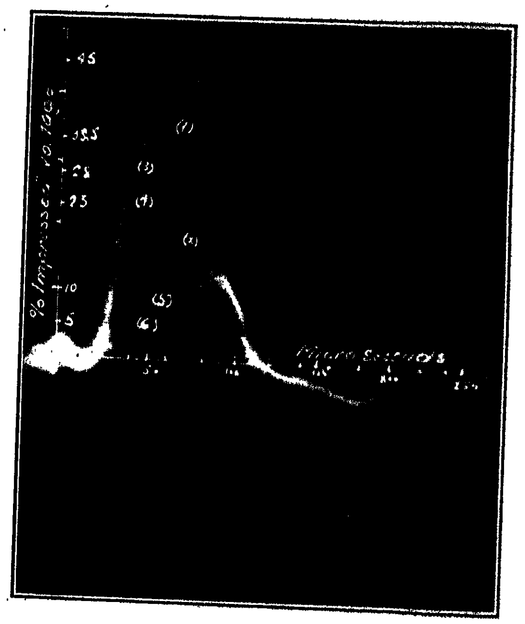

FIG. 7—OSCILLOGRAM SHOWING THE EFFECT UPON THE TRANSIENT NEUTRAL VOLTAGE OF SHUNTING THE REACTOR WITH DIFFERENT VALUES OF RESISTANCE

1 – R = Infinite (neutral grounded through reactor only)
2 – R = 25,000 ohms
3 – R = 11,000 ohms
4 – R = 6,000 ohms
5 – R = 1,200 ohms
6 – R = 580 ohms

cally be carried to any optional limit, but the influence of the resistor on the characteristics of the neutral impedance must be considered.

The effect of shunting resistance upon the voltage across the reactor is shown in Fig. 7. In support of the statement above, it is seen that the amplitude of the voltage decreases with decreasing shunting resistance. In order to limit the voltage to a low value the resistance

would have to be such that its losses would be high under short circuit and its proportions relatively large.

B. Reactor Shunted by Spark-Gap. The second method of preventing excessive voltage at the neutral is to shunt the reactor with a spark-gap. This method permits the voltage to rise to some safe predetermined value and then reduces it to zero. The voltage at which the gap would be set is determined by the insulation of

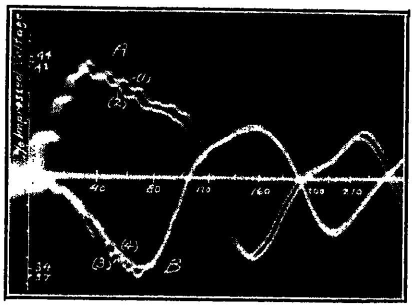

Fig. 8—Oscillogram Showing the Effect Upon the Internal Transformer Winding Transient of Shunting Neutral Reactor with Safety Gap

A —Voltage at 69 per cent of winding from neutral
B —Voltage at 36 per cent of winding from neutral
1,3—Neutral grounded through reactor shunted with safety gap
2,4—Neutral solidly grounded

the reactor. The super-imposed transient accompanying the gap discharge has no damaging effect upon circuits of as long a time constant as that of the transformer winding. The effect of this transient is shown by the oscillograms in Fig. 8, where the resulting voltages at 36 or 69 per cent from neutral are compared with those with the neutral solidly grounded. The increase in voltage is 7 to 9 per cent over that with solidly grounded neutral or about 3 per cent of the impressed voltage.

The principal objection to this device is the liability of the same impulse that causes the gap to discharge also causing a line flash-over or a line to neutral fault, thereby maintaining the arc across the gap with dynamic current and shunting out the reactor at the time when its service is required.

C. Reactor Shunted by Lightning Arrester. Proceeding as in the case of the shunting spark-gap, the proper lightning arrester for protecting the insulation of the reactor was selected. An arrester of the valve type is ideal for this application. The properties of this arrester are well known.[4] Its impedance is practically infinite up to the discharge voltage where it is instantly reduced to a relatively low value. It has a definite cut-off voltage which assures that none of the dynamic current will be by-passed through it. In applying the arrester it is necessary only to fix the cut-off voltage slightly in excess of the dynamic rise of voltage. By so doing, the maximum discharge voltage can be limited to approximately 2.5 times the dynamic voltage even when discharging large currents.

The effect of the arrester discharging on the transient voltage in the transformer winding is shown in Fig. 9. This illustration is a comparison of the voltages with solidly grounded neutral with those when an arrester bridges the reactor. The increase in voltage is of the order of 2 to 3 per cent over that with the neutral solidly grounded.

This method of reducing the neutral voltage has other advantages in addition to those mentioned. It employs a standard protective device which requires no special consideration or calculation for its application.

D. Reactor Shunted with Resonant Circuit. A series capacitance and inductance circuit was connected in parallel with the neutral reactor and the constants proportioned so as to be in resonance at the frequency of the transient voltage existing at the reactor terminal. This circuit offers a very low impedance path to the surge current and shunts it directly to ground, but has a very high impedance at normal operating frequencies. With the surge current determined largely by the impedance of the transformer winding, the two elements are proportioned so as to give a minimum rise in voltage at the neutral and keep the drop across each within safe limits.

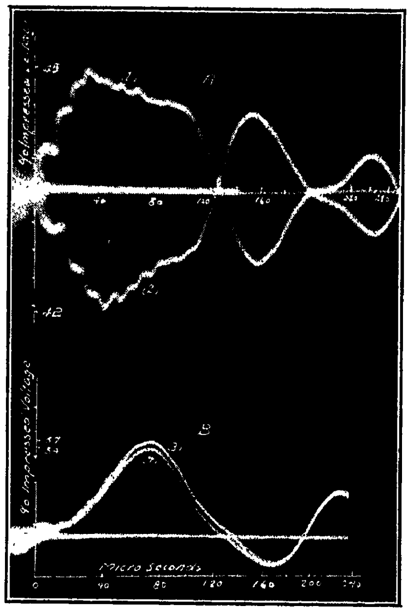

Fig. 9—Oscillograms Showing the Effect on the Internal Transformer Winding Transient of Shunting Neutral Reactor with Lightning Arrester

A —Voltage at 69 per cent of winding from neutral
B —Voltage at 36 per cent of winding from neutral
1,3—Neutral grounded through reactor shunted with lightning arrester
2,4—Neutral solidly grounded

In the experimental application the circuit was proportioned so that the rise in voltage at the neutral due to lightning would not exceed twice the dynamic voltage under the most severe conditions. Fig. 10 shows oscillograms of the voltage at two internal points in the winding and at the neutral. In oscillogram *A* the voltages resulting from the reactor being shunted with the resonant circuit are compared with the voltages with the neutral solidly grounded. The maximum amplitudes of the voltage at each point are practically

equal for the two conditions, and the shape of the volt-time curves are practically identical, except that with the reactor shunted by the resonant circuit the axis of oscillation is shifted upwards on account of the drop through the circuit. In oscillogram C the voltage at the neutral with the reactor alone and with it shunted with the resonant circuit are compared. The amplitude of the voltage in the latter case is reduced to approximately one-sixth of that when the neutral is grounded through the inductance only.

Conclusions

a. Transformers with isolated neutral are subject to transient voltages of a high order from lightning surges throughout the winding and at the neutral and require full insulation to ground for the entire winding.

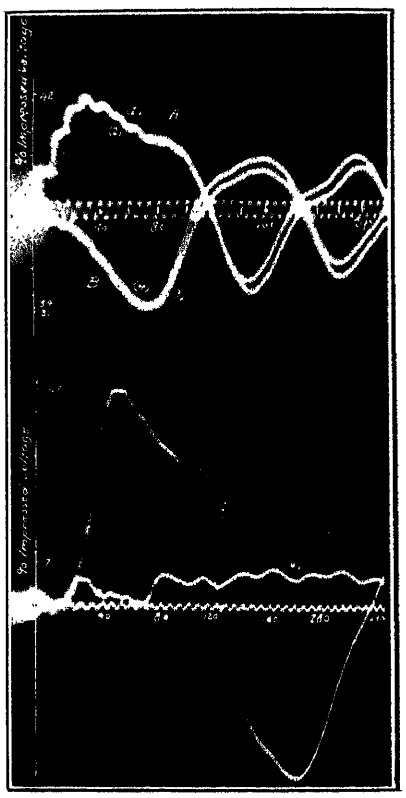

Fig. 10—Oscillograms Showing the Effect Upon the Internal Transformer Winding Transient of Shunting Neutral Reactor with Auxiliary Resonant Circuit

A —Voltage at 69 per cent of winding from neutral
B —Voltage at 36 per cent of winding from neutral
C —Voltage at neutral
1, 3 & 6—Neutral grounded through reactor shunted with resonant circuit
2, 4—Neutral solidly grounded
5—Neutral grounded through reactor only

b. If the transformer has the neutral grounded through a resistance of not over 400 to 500 ohms, the internal transient voltage stresses exceed those for solidly grounded neutral by only a small percentage. Therefore, in general, the same rules regarding the grading of the insulation to ground apply as for solidly grounded neutral taking due account of the dynamic rise in voltage due to short circuit.

c. The drop in voltage across a neutral resistance is not in phase with the transformer impedance drop, a larger value of resistance is required to limit the current to a given value and consequently a higher voltage appears at the neutral than when the neutral is grounded through an inductance.

d. Transformers with the neutral grounded through a reactor may be subjected to high oscillatory voltages due to lightning and unless some means are provided for reducing this voltage the transformers must have full insulation.

e. The transient voltage as a result of lightning surges in transformer windings grounded through a reactor can be reduced to within a small percentage of that with solidly grounded neutral and the voltage at the neutral maintained at a safe value by shunting the reactor with resistance, with a safety gap or with a lightning arrester or with an auxiliary resonant circuit.

f. In order to obtain the desired characteristics with a shunting resistance, the resistance has to absorb a relatively large amount of energy which may result in its having proportions comparable to that of the reactor.

g. The use of safety gaps appears undesirable on account of the possibility of maintaining the transient arc when the system is operating under short-circuit conditions.

h. Lightning arresters offer advantages in that they have low impedance to lightning transients of high amplitude and practically infinite impedance to the short-circuit currents, are a standard piece of apparatus, relatively small in size and easy to apply, requiring only a knowledge of the short-circuit voltage drop across the reactor.

i. An auxiliary resonant circuit offers an effective means of reducing and maintaining the transient to a relatively low value, approximately that with solidly grounded neutral, and at the same time offer a high impedance to normal frequency current.

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Discussion

A. W. Copley: This paper is valuable in that it gives the results of actual tests on a commercial bank of transformers with various kinds of grounding devices inserted between neutral and ground and with surges of known value impressed across them. The interest in the paper does not center about the use of terms or about the theories involved but rather about the practical results of the tests from the standpoint of the operating man.

Many years ago the ungrounded neutral transmission system was not uncommon. Soon after the advantages of the grounded neutral system were developed most transmission systems had their neutrals solidly grounded. The one disadvantage of the solidly grounded neutral did not appear until systems grew to such a size that it became important. This is the large flow of ground current occasioned by fault to ground on the transmission system. As this feature developed means were sought to reduce the ground current at the same time retaining the advantages of the neutral ground. Resistances were placed in the neutral, then other means, such as reactance, Peterson earth coils and other resonant circuits were used. The effect of these devices on neutral ground current and on the distribution of normal frequency voltage has been naturally well understood. The effect which might be produced by lightning surges has, however, been open to question and the tests which have been reported by Messrs. Vogel and Hodnette give very valuable evidence as to what takes place under these surge conditions. The conclusions which they have reached appear to be logical when a study of the results is made.

The neutral grounded through reactance shunted by a resonant circuit apparently gives good results. The neutral grounded through reactance shunted by a lightning arrester also gives results which appeal to the operating engineer.

L. V. Bewley: The test circuit used in the paper (Fig. 2), shows some lumped resistances Z_s of approximately 450 ohms, which the authors refer to as "lumped surge impedances." The implication is that these resistances behave as true surge impedances, and that the circuit is therefore the equivalent of an actual transmission line. It is the purpose of this discussion to show to what extent their test circuit fails to duplicate the functioning of an actual line. If this fact was understood by the authors they should have called the resistance a *resistance* and not a "lumped surge impedance," as otherwise the terminology is rather misleading.

If any generalized impedance network $Z(p)$, where $p = d/d\,t$ is the time derivative operator of operational calculus, be connected to the terminal of a transmission line of surge impedance $z = \sqrt{L/C}$, and an incident wave $e = f(t)$ is sent down the line where t is counted from the instant that e arrives at the network, then the total potential at the terminals of the network is

$$e_o = \frac{2\,Z(p)}{Z(p) + z}\,e \tag{1}$$

Therefore the criterion that a test circuit shall duplicate the functioning of a transmission line, is that the total voltage across the test piece shall be expressible in the form of Equation (1), in which e is independent of the connected impedance network.

Solving the circuit of Fig. 2 in the authors' paper for the voltage across the test piece $Z(p)$, (in this case the transformer) there is (calling $Z_s = 3\,z'$)

$$e_o = \frac{2\,Z(p)}{(R + z') + Z(p)} \left\{ \frac{R}{2\,L} \frac{p\,E}{p^2 + \dfrac{R}{L}\dfrac{z' + Z(p)}{R + z' + Z(p)}\,p + \dfrac{1}{L\,C}} \right\} \tag{2}$$

where E is the voltage to which the condensers were charged.

Now putting

$$z = (R + z') \tag{3}$$

and

$$e = \frac{R}{2\,L} \left\{ \frac{p\,E}{p^2 + \dfrac{R}{L}\dfrac{z' + Z(p)}{z + Z(p)}\,p + \dfrac{1}{L\,C}} \right\} \tag{4}$$

Equation (2) superficially takes the same form as Equation (1), *but* e is not independent of $Z(p)$ and therefore the circuit is not a true representation of a traveling wave condition.

However, if the impedance $Z(p)$ is at all instants considerably greater than z, then approximately

$$e = \frac{R}{2\,L} \left\{ \frac{p\,E}{p^2 + \dfrac{R}{L}\,p + \dfrac{1}{L\,C}} \right\}$$

$$= \frac{n + m}{n - m}\left(\epsilon^{mt} - \epsilon^{nt}\right)\frac{E}{2} \tag{5}$$

where

$$\left.\begin{aligned} n &= \frac{R}{L} + \sqrt{\frac{R^2}{L^2} - \frac{4}{L\,C}} \\ m &= \frac{R}{L} - \sqrt{\frac{R^2}{L^2} - \frac{4}{L\,C}} \end{aligned}\right\} \tag{6}$$

But to make use of this possibility necessitates making R so small as to decidedly reduce the efficiency of the impulse generator.

The authors make a distinction between a resistance having a constant characteristic (which they call a *resistance*) and a resistance having a variable characteristic (which they call a *lightning arrester*). Apparently this distinction has accounted for many years of misunderstanding over the relative merits of shunting ordinary power limiting reactors with resistors. It is therefore worth mentioning that the resistors which have always been used by the General Electric Co. for shunting power limiting reactors have been "lightning arresters" according to the Vogel-Hodnette definition. Reference may be made to *Shunt Resistors for Reactors* by F. H. Kierstead, H. L. Rorden and L. V. Bewley, A. I. E. E. TRANS., Vol. 49, p. 1161, and to the discussion of that paper by F. J. Vogel.

K. K. Palueff: Since January 1929, the attention of the Institute has been called to the phenomena of transient voltages within transformer windings by five papers and considerable discussion.

There are three principal subjects of the above study—the core type transformer, the shell type transformer, and the non-resonating type of transformer. The behavior of these transformers, with neutral isolated or grounded either directly or through various impedances, was described in the above papers.

The two groups of contributors at the beginning entertained practically diametrically opposite views on the phenomena which take place within the winding of an ordinary transformer, particularly of the shell type. It is gratifying to find that the differences in opinion are gradually disappearing.

We were confident that the initial voltage distribution produced by a steep wave front causes an extremely high-voltage concentration at the line end of windings having either wide coils and a short stack or narrow coils and a long stack.

Mr. Hodnette's group was confident that in a short stack of wide coils, which is typical of shell type transformers, the initial or electrostatic voltage distribution is practically uniform, and that such uniform distribution is obtained by properly proportioning the windings [1] and by the slanting of the front of the inci-

1. *Effect of Surges on Transformer Windings*, by J. K. Hodnette, A. I. E. E. TRANS., Jan. 1930, p. 72.

dent wave by means of the electrostatic capacitance of the condenser type bushing.[2] That the bushing has an absolutely negligible effect on the transient voltages in a transformer is shown in the TRANSACTIONS for July 1929 on pp. 699 and 700.

In my discussion of Mr. Hodnette's paper of a year ago, I suggested that further study of the phenomenon would bring us to complete agreement on this subject. I am delighted to find that Mr. Hodnette's latest tests have confirmed this suggestion. This can be seen from Fig. 1 of the present discussion.

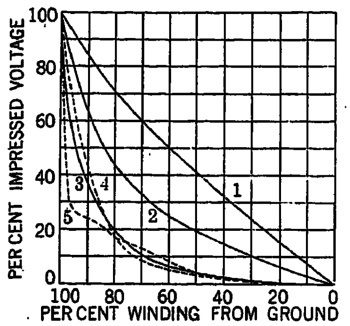

FIG. 1—INITIAL VOLTAGE DISTRIBUTION

Hodnette's Data
1—Original
2—Second
3—Latest
Palueff's Data
4—Order of magnitude, core and shell type transformers
5—Test on shell type transformer

Curve 1 represents Mr. Hodnette's original conception of initial voltage distribution in shell type transformers. It is taken from Fig. 7 of his paper presented in August 1929. Curve 4 represents our conception of the order of magnitude of the initial voltage distribution of the core and shell type transformer in general, and curve 5 shows the results of our test on a shell type transformer. These curves are taken from my papers of January and May 1929. Curve 2 is copied from Mr. Hodnette's discussion of my paper of last May, and represents the result of his test on a 30,000-kv-a. shell type transformer.

Curve 3 is a copy of the initial voltage distribution found by Mr. Hodnette in a 25,000-kv-a. shell type transformer, and published in the present paper as curve 1 of Figs. 3, 4, and 6. The above indicates that we have gradually come to a fairly good agreement as to the initial voltage distribution in shell type transformers. I say, "fairly good agreement," because in shell type transformers, due to the great width of the coil, the initial voltage distribution cannot be represented by a smooth curve as is done by Mr. Hodnette but actually has a saw-tooth shape, which accentuates the severity of the voltage concentration at the first two or three coils at the line terminal, as illustrated on p. 77 of my paper in the January 1930 TRANSACTIONS.

VOLTAGE TO GROUND—GRADED INSULATION

Another point of disagreement between the two groups of investigators is the maximum voltage to ground that can be created in solidly grounded or isolated-neutral shell type transformers when subjected to a lightning or switching wave.

We stated that the envelope of maximum voltages to ground in both core and shell type transformers is about the same and can be represented as shown here by curve 1 of Fig. 2. The other group of investigators at first expressed an opinion that a single wave cannot cause oscillations in shell type transformers. Later, Mr. Hodnette showed that the shell type transformer, even with solidly grounded neutral, oscillates in very much the same way as we have shown. He expressed a belief, however, that these oscillations do not cause the voltage to rise above a uniform voltage distribution (curves 2 and 3 of Fig. 2 of this discussion). This was in accord with his opinion that no lightning waves longer than 60 microseconds should be considered of importance, and that 5,000 cycles was the maximum natural frequency for shell type transformers. If these suppositions were correct, then it could be shown by means of the laws published by the writer in January 1929, that the voltage due to oscillation cannot rise above the straight line, and for this reason he felt confident that grading of the insulation between the high-voltage winding and the other parts of the transformer is permissible. Mr. Hodnette therefore gave curve 2 of Fig. 2 (this discussion) as the maximum possible voltage to ground in a shell type transformer that can be produced by a 60-microsecond wave. This was obtained by him from scaling the oscillograms in his paper. I have shown that more precise measurements of his oscillograms give curve 4 as a more accurate representation of the voltages found in his transformer. Besides, the wave he termed "60 microseconds," as recorded in his oscillograms, was actually only 47 microseconds. Furthermore, I expressed confidence that 5,000 cycles is not the upper limit of natural frequency of a shell type transformer, and that with a higher natural frequency the voltage will rise up to the limit shown by curve 1 of Fig. 2 (this discussion). I am glad that Mr. Hodnette has found a shell type transformer with natural frequency of 12,500.[3]

Mr. Hodnette must certainly agree that at such a natural frequency a 60-microsecond lightning wave will cause a voltage to ground as shown by curve 1 of Fig. 2. This is an inevitable conclusion from the above mentioned law which Mr. Hodnette evidently accepted, since he used it as an argument in favor of curve 3, Fig. 2. The law states that the voltage to ground will reach the above mentioned curve if a transformer terminal voltage is maintained at a given value for at least half a cycle of the natural frequency of a transformer. Very simple calculations show that should the terminal voltage, instead of being maintained during half of the period, decay to half of its value during that time, practically the same internal voltage will still be

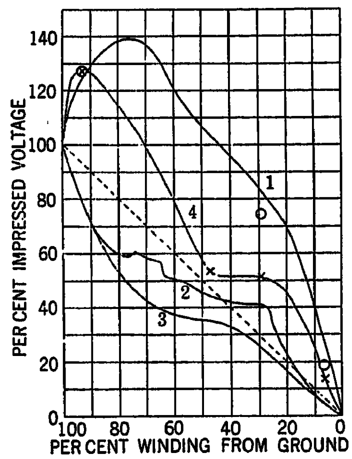

FIG. 2—MAXIMUM VOLTAGE TO GROUND DUE TO A SINGLE LONG TRAVELING WAVE

Paleuff's Data
1—Theoretical maximum. Points shown (circles) were scaled from Hodnette's oscillograms, with 250-microsecond wave in his Sept. 1929 paper
Hodnette's Data
2—Hodnette's first hypothesis (60-microsecond wave) from his Sept. 1929 paper
3—Hodnette's latest, from Fig. 3 of his present paper
4—No. 2 corrected according to Hodnette's present paper with 60- (actually 47-) microsecond wave shown in his Sept. 1929 paper

2. Discussion by J. F. Peters, A. I. E. E. TRANS., Oct. 1928, p. 1014.

3. Discussion by J. K. Hodnette, A. I. E. E. TRANS., January, 1930, p. 81.

reached, in case the oscillation contains higher harmonics. The oscillograms and the theory show that the oscillation of a shell type transformer, like that of a core type transformer, contains a great many harmonics.

The above considerations lead us to the conclusion that the grading of major insulation in solidly grounded transformers is a dangerous practise. The original conception of the phenomena by Mr. Hodnette led him to a diametrically opposite conclusion, as we see from curve 2 of Fig. 2. The actual observation of shell type transformer oscillations contradict his idea as was just shown. In addition, even some of Mr. Hodnette's associates do not agree that a wave longer than 60 microseconds is required to produce voltage above uniform voltage distribution in shell type transformers.

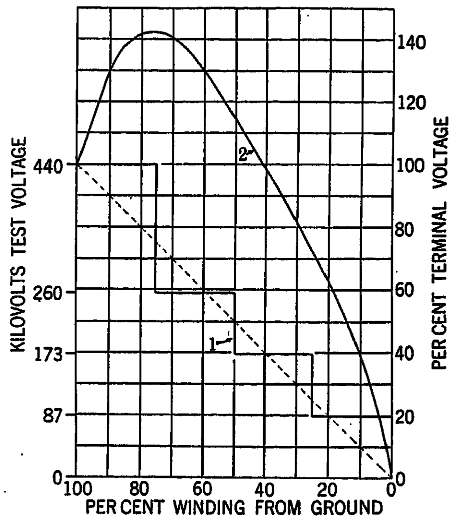

FIG. 3—COMPARISON OF VOLTAGE TO GROUND AND MAJOR INSULATION STRENGTH IN 220-KV. TRANSFORMER THAT FAILED DURING LIGHTNING

1—Graded insulation strength
2—Maximum lightning voltage to ground

For example, J. F. Peters states[4] "When the impulse is maintained for a considerable time, 10 to 20 microseconds, the voltage will penetrate into the winding and may overshoot the values beyond a uniform distribution. The amount the voltage overshoots depends to a considerable extent upon the initial distribution which in turn is a function of the physical proportions of the design." It should be noted that curve 2 of Figs. 3, 4, and 6 of Mr. Hodnette's paper show that the initial voltage distribution in a shell type transformer is extremely non-uniform. Furthermore, the failure of a 220-kv. transformer with graded insulation and solidly grounded neutral described by Mr. Floyd substantiates our theory. This transformer failed during lightning, in spite of the fact that the line insulation was coordinated with the insulation of the line group of the transformer, as was shown by Mr. Floyd and by my discussion of Mr. Floyd's paper. Fig. 3 illustrates the relation between the dielectric strength of that transformer as stated by Mr. Floyd and the voltage which should be expected in that transformer when subjected to lightning.

The grading of major insulation is permissible only in case the transformer is of the non-resonating type, as we have shown analytically, as well as experimentally, in the three papers presented to the Institute since 1929. The experimental results were obtained on commercial transformers with artificial lighting voltages of several hundred thousand volts. A short time ago, we were able to demonstrate that our experimental and theoretical conclusions apply equally well to lightning voltages of magnitude met in service. One of the 13,000-kv-a. 220,000-volt non-resonating transformers, built for the New England Power Company has been subjected to an artificial lightning test. This test consisted of repeated applications of voltage from one million two hundred thousand volts up to three million volts. The transformer was connected to the lightning generator by means of a few hundred feet of wire. In shunt with the transformer, fourteen 5¾-in. insulator disks were connected. Voltage waves of one-half microsecond front and of varied length (from 20 up to more than 120 microseconds) were applied, of values just below that necessary to arc-over the insulator strings, thus subjecting the transformer to the highest full lightning wave that could be experienced in service. Also, waves far in excess of the arc-over value of the strings were applied but of course were reduced to arc-over value by flash-over of the strings. Cathode ray oscillograms were taken of a great many of these waves. These lightning tests were preceded and followed by complete A. I. E. E. acceptance tests, which included an induced voltage insulation test of 460 kv. The transformer passed all these tests successfully, and a thorough examination of the windings and insulation of the transformer did not reveal any sign of damage.

It should be noted that in accordance with proposed A. I. E. E. recommendations for coordination of transformer and line insulation, the above induced voltage test corresponds to line insulation of 14 disks.

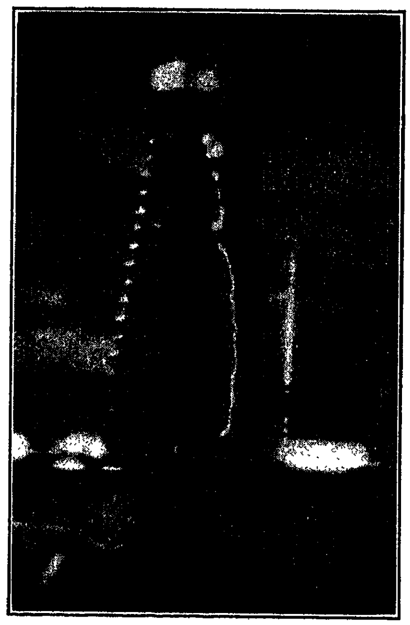

FIG. 4—ARTIFICIAL LIGHTNING TEST ON 13,000-KV-A. 220,000-VOLT TRANSFORMER

From the above it appears that Mr. Hodnette's group and ourselves will also reach complete agreement on the question of graded insulation in the near future, as we did on the electrostatic voltage distribution; because it seems beyond any doubt that our minds already run along the same channel. This may be best illustrated by parallel quotations from Messrs. Vogel and Hodnette's present paper and my paper on the same subject of last May, as well as my other contributions.

Vogel-Hodnette—(Page 63)

"The initial voltage distribution, Fig. 4 is practically the same irrespective of whether the transformer is solidly grounded, grounded through an impedance or completely isolated."

Palueff—(Page 1181, A. I. E. E. TRANS., July 1930)

"In ordinary power transformers, either of shell or of core type, the initial voltage distribution produced by a steep front of a

4. Discussion, A. I. E. E. TRANS., July 1929, p. 1008.

traveling wave is practically the same whether the neutral is solidly grounded or isolated."

(Page 1186)

"With a transformer grounded through an inductance the initial voltage distribution will be the same as in case of a solidly grounded transformer. . . ."

Vogel-Hodnette—(Page 63)

"This is expected from the initial distribution curve of Fig. 3 which shows that but a small percentage of the voltage exists in the portion of the winding near the neutral."

Palueff—(Page 1181)

"This occurs because at the first instant voltage concentrates across the line end of the winding, and the drop across a considerable part of the winding near the neutral end is only a few per cent of the total applied voltage."

Vogel-Hodnette—(Page 63)

"The final distribution is quite different from that with the neutral grounded. When the neutral is isolated and a surge is impressed, the winding tends to assume the same potential throughout."

Palueff—(Page 1181)

"The final voltage distribution in a transformer with isolated neutral, however, is radically different from that of a transformer with grounded neutral."

". . . Therefore all points of an isolated winding finally acquire a potential above ground equal to the terminal voltage . . . The line of final voltage distribution will serve as a line of equilibrium or axis for the oscillation."

Vogel-Hodnette—(Page 63)

"The amplitude of the oscillation at the neutral depends upon the magnitude of the terminal voltage and the relation of the length of the surge to the natural period of oscillation."

Palueff—(Page 1001, TRANS., July 1929)

"The amplitude of oscillation depends upon voltage of applied wave, the steepness of the initial (or electrostatic) voltage distribution, the steepness of the front of the traveling wave and the length of the tail of the wave."

(In addition to this a numerical relation was established between the above factors and natural period of a transformer oscillation and was presented principally in the form of a set of curves in my various papers.)

Vogel-Hodnette—(Page 63)

"When the transformer neutral is grounded through a non-inductive resistance, the axis about which the winding tends to oscillate is a straight line extending from the line to the neutral end of the winding. The voltage at the neutral will be raised to a value depending upon the value of neutral resistance, the relative effective impedance of the transformer winding and the length of the traveling wave."

Palueff—

The law stated in the first sentence is shown in my paper in the form of diagram V (Fig. 3, p. 1181 of July 1930 TRANS.).

The law stated in the second sentence is stated also in the form of diagrams, (Figs. 10, 11, and 12, pp. 1184 and 1185).

Vogel-Hodnette—(Page 64)

"With larger values of grounding resistance, the increase in voltage becomes more pronounced, particularly in the portion of the winding near the neutral."

Palueff—(Page 1185 TRANS., July 1930)

"The effect (the increase of the voltage due to the increase of resistance in the neutral) is greatest at the neutral point; the effect near line end is small."

Vogel-Hodnette—(Page 64)

"The oscillatory voltage occurring across the reactor is a function of the relative inductance of the transformer and reactor, and the relative length of the traveling wave. The higher the ratio of the reactor inductance to transformer inductance, the greater will be the rise of voltage at the neutral."

Palueff—

The same is stated in my paper on page 1186 (TRANS., July 1930) in the form of an equation, and by Fig. 14, which gives the numerical relation between the maximum voltage from neutral to ground as a function of the ratio of the neutral inductance and transformer inductance.

The same sort of similarity exists between my first two papers (Jan. and May 1929) and Mr. Hodnette's first paper (Sept. 1929).

Some further similarity could be established throughout the rest of the present paper, but the above is believed to be sufficient to show that fundamentally we are in agreement and that it is just a matter of further tests by Messrs. Vogel and Hodnette to bring their experimental results into as complete accord with ours as are their theoretical conceptions of the phenomena at present.

The "conclusions" arrived at in the present paper, except for the statement regarding the advisability of using graded insulation, appear to be in complete accord with our conclusions. The lightning arrester used at the neutral is the only one variety of the impedor, as I explained in my closing discussion of last May, TRANS., July 1930, p. 1196. This was applied by us in practise quite some time ago.

Grounding the neutral through an auxiliary resonating circuit, suggested in the last paragraph of the conclusions, is objectionable for the following reasons. First, because of the possibility of excessive voltages due to resonance in the circuit in case of a damped oscillation being applied to the transformer. Second, the natural period of oscillation of the neutral changes with the mode of transient voltage excitation of the three units of the transformer bank. Therefore, a circuit at the neutral selected to resonate for one condition of excitation will not resonate when the excitation changes, and therefore will become ineffective as a voltage reducing device.

It is regrettable that the authors have not published the oscillogram of the transformer terminal voltage wave that produced the internal oscillations shown in the paper. It is also unfortunate that only two points of the winding in the case of a grounded neutral and three points of the winding in the case of an isolated neutral were investigated, as such a number of points is not sufficient to allow drawing curves such as curve 2 of Figs. 3 and 4 of the paper with proper accuracy. As I pointed out in previous discussions, when tests are made on windings with wide coils it is particularly important that the voltages are measured not only on the outside edges of the coils but also on the inside, since the measurement on the inside edges discloses decidedly higher stresses than those found on the outside. Of course I appreciate that in a completely assembled shell type transformer the inside edges are not accessible unless special means are provided.

E. L. White: It appears that the most desirable form of impedance is a reactor protected by a sphere gap. I should like to ask Mr. Vogel whether or not experiments were made with resistances cut in series with the gap to limit the flow of dynamic current.

F. J. Vogel: Mr. L. V. Bewley's discussion is particularly interesting in that part referring to the surge generator. Strictly speaking the lumped line surge impedance Z_s is a resistance, but in the tests made, with a few exceptions, the assumption that the test circuit used would act similarly to a transmission line circuit was justified. An endeavor to show the reasons for this is given as follows:

First, the wave of the voltage across the resistance R was within a few per cent of being identical whether the transformer was connected or not. Under these circumstances the sole impedance between the surge generated and the transformer was in effect the 450-ohm resistance. This fact states definitely that the surge generated is independent of the connected transformer impedance and, therefore, the surge generator circuit used corresponds in effect to a transmission line connected to the transformer.

Second, the fundamental equation for the voltage across the transformer or load, with reference to the surge generator circuit, is

$$e_o = \left[\frac{Z\,(p)}{z' + Z\,(p)}\right]\left[\frac{\dfrac{R\,(z' + Z\,(p)\,)}{R + z' + Z\,(p)}}{\dfrac{1}{c\,p} + L_p + \dfrac{R\,(z' + Z\,(p)\,)}{R + z' + Z\,(p)}}\right] E \qquad \textbf{(A)}$$

No doubt Mr. Bewley arrived at his Equation (2) from the equation above. The first term represents the proportional part of the voltage across the resistance R that is across the transformer. The second term represents the voltage across the resistance R and therefore is the important term. Obviously this second term can be expressed as

$$\frac{\left(\dfrac{1}{c\,p} + L_p + R\right)\dfrac{z' + Z\,(p)}{R + z' + Z\,(p)}}{\dfrac{1}{c\,p} + L_p + \dfrac{R\,(z' + Z\,(p)\,)}{R + z' + Z\,(p)}} \quad \frac{R}{\dfrac{1}{c\,p} + L\,p + R} \qquad \textbf{(B)}$$

With reference to the indicial impedance $Z\,(p)$, $L\,p$ is negligible; furthermore the capacity of the surge generator is made large so that relative to both R and $Z\,(p)$ the term $\dfrac{1}{c\,p}$ is of secondary importance. The resistance R used is generally considerably greater than z'. These relations state the physical fact that the load network current flows through the surge generator capacity with a relatively small impedance drop. The function of the resistance R is to discharge the surge generator capacity at a rate according to the surge that is desired to be generated. The second term in Equation (A) may then be approximately given as

$$\left[\frac{R}{-\dfrac{1}{c\,p} + L\,p + R}\right].$$

This corresponds to the voltage generated without a load on the surge generator. We can now see the similarity between Equation (A) simplified and the fundamental equation for a transmission line as given in Equation (1) by Mr. Bewley.

$$e_o = \left[\frac{2\,Z\,(p)}{z' + Z\,(p)}\right]\left[\frac{R}{\dfrac{1}{c\,p} + L\,p + R}\right]\frac{E}{2} \qquad \textbf{(C)}$$

$$e_o = \frac{2\,Z\,(p)}{z' + Z\,(p)}\,e \qquad \textbf{(D)}$$

The latter term, e, then represents the surge voltage on the transmission line, and in combination with the first term combines to form the fundamental equation for the transmission line.

Referring to Mr. Bewley's comments with regard to the resistance units used for shunting reactors, we believe that previous to the paper mentioned, no description of these resistances was offered. It is also to be noted that thyrite is a fairly recent development and is also used as lightning arrester material. It is also believed that resistances, whether of this type or not, were advocated for many years.

J. K. Hodnette: The subject matter given in Mr. Palueff's discussion has largely been covered elsewhere. It deals with impulse transients as a whole, rather than the particular subject of this paper. To prevent repetition it will not be developed to any extent here. Reference is made to discussions in the TRANSACTIONS, January 1930, p. 75, and July 1930, p. 1190. The authors' opinions on the matter have not changed from those expressed in these discussions, although Mr. Palueff interprets them to the contrary.

The positions expressed by him as being diametrically opposite with respect to the views on the phenomena, in reality are and have been different, principally, only in the hypothesis taken at the outset. That is, the characteristics of the impressed surge. In our experiments we have used a surge of characteristics dictated by field tests on natural lightning as being the worst, with respect to the stresses produced, that is ever expected to exist under service conditions. This wave is one that rises to maximum in one microsecond and decreases to half value in 60 microseconds. To establish the logic of this hypothesis it is necessary only to refer to the papers on lightning investigation published in the TRANSACTIONS during the past two years.

Mr. Palueff, on the other hand, has adopted a surge of great if not infinite length. Since no such wave can exist in practise, there appears to be little justification for such a hypothesis. Mr. Palueff apparently recognizes this fact and in his papers states that for finite waves the stresses are not so great, but gives no direct data as to how great they are.

If Mr. Palueff is interested in bringing about an agreement between his data and those published by ourselves and other experimenters, he may readily do so by adopting the above hypothesis. As previously pointed out, he cannot hope to arrive at conclusions or results representative of actual existing conditions if his hypothesis is not consistent with these conditions.

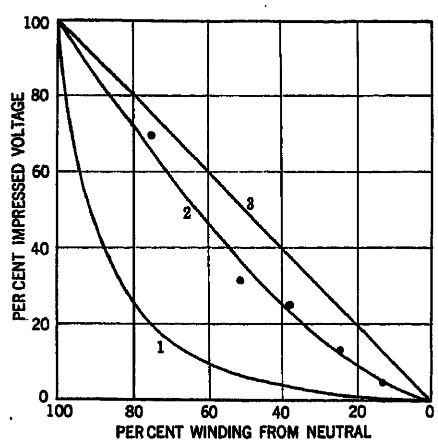

FIG. 5—VOLTAGE TO GROUND IN A SHELL TYPE TRANSFORMER PRODUCED BY A 100-MICROSECOND SURGE

1. Initial voltage distribution
2. Maximum voltage by oscillator
3. Final or steady state of distribution

We object to Mr. Palueff's misinterpretation of our test results. Reference to the discussions mentioned above and the papers discussed will clear these points. This applies to his Fig. 1 showing the evolution of the initial voltage distribution from practically a straight line to that illustrated as curve 3 which agrees with his conception of what the initial distribution should be. There has been no evolution of opinion on this subject. Test data only have been presented, representing a number of different transformers. Mr. Palueff has selected three curves from these and attempted to convey the idea of a changing opinion on our part.

With reference to the natural frequency of transformers, we are quoted as stating that 5,000 cycles was the maximum natural period of shell type transformers. No such opinion can be found in any of our publications. In addition, Mr. Palueff speculates that a 60-microsecond wave would produce a voltage to ground as shown on curve 1 of his Fig. 2 in a transformer having a natural period of 12,500 cycles. Actually the voltage is that shown in Fig. 5, of this discussion, which does not alter but confirm our conclusions.

Whether or not the grading of insulation is a safe practise is

best answered by the service record of the transformers, for that is the true criterion of the sufficiency of a design. Our conclusion in this respect is forcefully illustrated by the fact that there is no record of failure to ground of any transformer built by the company with which the authors are associated in the internal or graded groups. Evidently Mr. Palueff does not understand this system of grading insulation, nor is he in possession of the facts relative to the failure of the transformer reported by Mr. Floyd.

We cannot agree with Mr. Palueff that shunting the grounding reactor with a resonant circuit is objectionable. Irrespective of how an oscillation is produced at the transformer neutral the resonant circuit offers a low impedance path to ground. The tuning of this circuit can be made sufficiently broad to accommodate any variation in the frequency produced by various modes of excitation, which our tests indicate to be small.

Regarding Mr. White's question, no tests were made with resistance in series with the discharge gap across the reactor, as the characteristics can be readily obtained by combining the data for the shunting gap alone with that for the shunting resistance. The former apply up to the time the gap discharges, after which the latter applys since the gap resistance is negligible where the current is relatively large. The objections to such a scheme are the same as for a shunting resistor, that is, it would have to have sufficient thermal capacity to carry its share of the short-circuit current until the fault is removed. This would require a fairly large resistor. Under ideal conditions this scheme would approach the characteristics of a shunting lightning arrester.

New Trends in Mercury Arc Rectifier Developments

BY OTHMAR K. MARTI[1]
Member, A. I. E. E.

Synopsis.—Research investigations conducted by engineers as well as physicists during the last few years have resulted in notable improvements in the mercury arc rectifier, in particular with reference to backfire protection and voltage regulation as well as improved manufacturing methods. These improvements made it possible to build rectifiers of very large current capacities as well as for very high voltages. The basic principle of rectification is briefly reviewed in order to explain the results obtained with the aid of these improvements. Methods of testing rectifiers have also been improved on and new ones developed. Standard parts are now used for different rectifiers up to the largest capacities. An account is given of notable recent rectifier installations for city subway service, for a portable street-railway substation, radio transmission, electrolytic zinc refining, and for Edison systems.

When the steel-enclosed mercury arc rectifier became available to users of direct current, it entered into keen competition with rotary converters and motor generators and presents over the latter a number of advantages now well-known to operating engineers. In the last few years the use of rectifiers has been extended to fields which may be designated as their own in that they comprise applications for which rotary converters or motor generators are either costly and inefficient or not obtainable. One outstanding example is the case of 3000-volt direct current traction where two 1500-volt machines have to be used in series on account of the limitations of commutators, resulting in very large conversion losses and a complicated operating procedure. Another promising field for rectifiers is the electro-chemical industry, where certain processes require voltages as high as 12,000 volts, for which no high-voltage source of direct current of the required capacity was available until the advent of the high-capacity mercury arc rectifier. The steel-enclosed rectifier is also used at present for radio transmission, where a single high-voltage unit replaces numerous vacuum tubes or complicated and delicate mechanical converting equipment.

It is not generally known that the modern steel-enclosed rectifier is a product of the skill not only of the engineer but largely also of the physicist and, to a lesser extent, also of the chemist. Very little has so far been published about the work done by physicists on the mercury arc and comparatively scant literature is available to power engineers, traction engineers, and chemical engineers, in spite of the fact that during recent years they have been using rectifiers in increasing numbers in all parts of the world. It is not intended to give here a complete account of the theory of rectification, but a brief explanation of the valve action of the rectifiers will be given in order to explain some of the latest developments.

Theory and Design

In order to explain simply the principle of the rectifier, a single-phase two-anode rectifier set is usually considered. Such a rectifier is shown schematically in Fig. 1. Each anode carries the whole current for the half cycle during which it is positive with respect to the cathode, whereas for the other half of the cycle it carries no current. This is due to the property of the anode of preventing the flow of electric current in one direction while permitting it in the other direction.

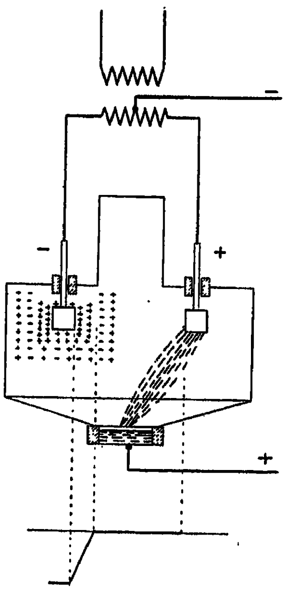

Fig. 1—Single-Phase Two-Anode Rectifier Set and Diagram of Voltage Between Anodes

This alternation of presence and absence of current on each anode is repeated once for every cycle so that, for a 60-cycle alternating-current supply, it is repeated 60 times per second. During this operation, the voltage between the two anodes is equal to the whole voltage of the transformer secondary, whose peak value is over twice the d-c. voltage. In the case of a 13,000-volt radio transmission rectifier, described below, the mercury vapor between the two anodes must, therefore, be able to withstand over 26,000 volts without breaking down.

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1. Chief Engineer, American Brown Boveri Co., Inc., Camden, N. J.

Presented at the Pacific Coast Convention of the A. I. E. E., Portland, Oregon, September 2-5, 1930.

The physical phenomena which produce this valve action are the whole secret of the operation of the rectifier and extensive investigations were carried out by physicists in cooperation with engineers in order to elucidate this action. It is not immediately apparent why the current flows between the anodes and the cathode, under the action of a potential difference of only about 25 volts, instead of between the anodes to which the potential difference applied may be 1000 times as great. The passage of current is due to the motion of positive ions and negative electrons traveling freely between the cathode and whichever anode is at a positive potential. The other anode, which is at that time negative with respect to the cathode, is at too low a temperature for emitting electrons. Since it is charged negatively it continually repels the free electrons moving about inside the cylinder, and at the same time attracts the positively charged mercury ions which therefore concentrate around the anode and form all around it what is called a positive space charge which will insulate it for considerable voltages. The actual thickness of this layer, represented by plus signs in Fig. 1 varies in proportion to the voltage. The voltage diagram below Fig. 1 shows how it localizes the voltage drop between the anodes with a very high gradient in the immediate neighborhood of the negative anode, while outside of the space charge the electrons and positive ions move as if there were no potential difference present between the two anodes.

All insulated metallic parts of the rectifier which are in contact with the mercury vapor, receive a negative charge due to the impact of numerous free electrons present in the rectifier tank. Those parts, and also any parts which are maintained at a negative potential with respect to the cathodes, act like the negative anode in that they surround themselves with a layer of positive ions, which layer insulates those parts and protects them from contact with the rectifying arc. It is for this reason that it is possible to build rectifiers with a metal enclosure, in which, also, the arc is guided by metallic funnels and, in the vicinity of the anodes, by metallic anode shields. Protected by this space charge, the different metallic parts act as if they were made of insulating material.

If for any reason the space charge surrounding the negative anode is broken down, the ions and electrons will then circulate between the two anodes, impelled by a potential difference which is no longer 25 volts but 26,000 volts. The secondary of the transformer is actually short-circuited by the arc and a heavy short-circuit current circulates between the anodes. This phenomenon is called an arc back or back-fire. The causes of the breakdown of the space charge around the negative anode are not fully understood. It is, however, well established that a back-fire may be caused by poor vacuum, condensation of liquid mercury on the anode or by impurities of the anode material. The anodes are usually made of very pure iron or graphite, which materials do not emit electrons at the operating temperature of the anode. Foreign particles on the surface of the anodes may, however, become incandescent and emit electrons. Condensed mercury, which emits electrons at a relatively low temperature will also produce a breakdown of the space charge. If the short-circuit current following the breakdown volatilizes the foreign particle, the space charge is reestablished during the next half cycle, and the valve action is restored, which phenomenon is called a silent back-fire. If the breakdown is maintained, however, the protective equipment with which the rectifier is provided will disconnect it from the a-c. line, the valve action is immediately restored, in less time than the breaker requires for reclosing, and the rectifier is again ready to take load.

Engineering Developments

The danger of breakdown of the space charge increases with the capacity of the rectifier so that special means had to be devised for insuring continuity of the valve action of the rectifier. The most important improvement along this line was obtained by means of screens introduced into the arc path in the vicinity of the anodes. These screens may be made of iron or graphite in the shape of concentric rings or wire meshes, and may be solidly connected to the anode shields or insulated from them, or else energized by an outside source of electric potential. When designing such screens, care must be taken that they do not increase the voltage drop in the arc. Following is a brief explanation of the action of these screens:

When an anode is carrying current, its screen takes its potential from the arc and is, therefore, at a lower potential than the anode. When the anodes cease to carry current, the screen retains its potential for a short time, during which it is negative with respect to the anode. It therefore attracts the positive ions and maintains the space charge at the instant when the anode ceases to be positive, at which time the tendency to back-fire is most pronounced.

Since the introduction of these screens, it has become possible to build rectifiers for very high current capacities per anode at medium high voltage and also rectifiers for very high voltages, while keeping their dimensions within reasonable limits. The progress made in this respect is evident when one considers that rectifiers for traction purposes now in operation are rated as high as 3,000 kw. nominal rating at 600-650 volts and 2,000 kw. at 3,000 volts; cylinders used for electro-chemical purposes range from 7,200 kw. at 500 volts to 2,000 kw. at 8,000 volts; for radio transmission, only 400 kw. at 13,000 volts has so far been required.

With the broadening of the applications of rectifiers, a number of problems not directly connected with the operation of the rectifiers themselves had to be considered. One problem which gave some concern to operating engineers a few years ago is the problem of

interference with commutation circuits due to the ripple in the direct current delivered by the rectifier. This problem was carefully studied at the outset and may now be said to be completely solved. As may be seen from the technical literature, equipment was immediately developed to eliminate any case of telephone interference that may occur so that no troubles need be feared from this source any longer.

In order to reduce the effect of back-fires on the rectifier circuit, large capacity rectifiers are equipped not only with quick-acting d-c. breakers but also with high-speed a-c. breakers. Oscillographic records taken in service show that with modern a-c. breakers back-fires can be interrupted in less than 8 cycles after the trip coil of the breaker is energized. The rectifier is put back into service immediately after the interruption.

Another recent development of great value is the regulation of the d-c. voltage of the rectifier by controlling the electric field inside the rectifier. This is obtained by controlling the point of the cycle at which the anodes pick up current in rotation.* This control is obtained by means of the energized screens mentioned above. In normal operation the arc is transferred from one anode to the next when the voltages applied to the two anodes are equal, or, in other words, at the point of intersection of their voltage waves. By retarding the point at which each anode picks up current, instead of using only the peak of the voltage wave for each anode, the firing occurs partly on the peak and partly on the sloping part of the voltage wave. The average d-c. voltage of the rectifier is therefore reduced and it is possible to vary it over wide limits without changing the value of the applied a-c. voltage. This will be made the subject of a later paper.

In the case of rectifiers provided with interphase transformers it is also often desirable to eliminate the abrupt rise of the voltage curve at no load. This voltage rise is present because, when the load decreases below a certain value, the third-harmonic flux in the interphase transformer decreases below its saturation value, thereby making the interphase transformer ineffective. This is easily remedied by providing the interphase transformer with an exciting winding permanently connected to a bank of very small auxiliary transformers connected so as to give a voltage which is a third-harmonic of the fundamental wave.

Not only in the design of rectifiers has considerable progress been made, but also in the measuring methods used with them. This was made necessary by the increased capacities of rectifier cylinders. In the past, the losses have been measured by means of a wattmeter having its current coil inserted in one anode lead and its voltage coil connected between the same anode and the cathode. The voltage drop in each anode can also be determined directly by taking an oscillogram and computing the average of the oscillographic curve. Since, in a rectifier, the losses are independent of the output voltage, they become large compared to the output at very low voltages, and it is possible to measure them accurately by means of the input-output method. The output is easily determined by means of d-c. instruments while the input is determined by measuring the power output of each phase of the transformer secondary, which requires six wattmeters for a six-phase connection. With the very large anode currents encountered at present, it becomes necessary to connect the wattmeter current coil to the anode leads by means of current transformers. Since the anode currents are uni-directional the cores of the current transformers become saturated and their accuracy is impaired. This inconvenience can be avoided and the number of wattmeters reduced to three, by the following novel method:

Each wattmeter current coil is connected to a current transformer having two primaries inserted in opposition into the leads of two anodes working half a cycle apart.

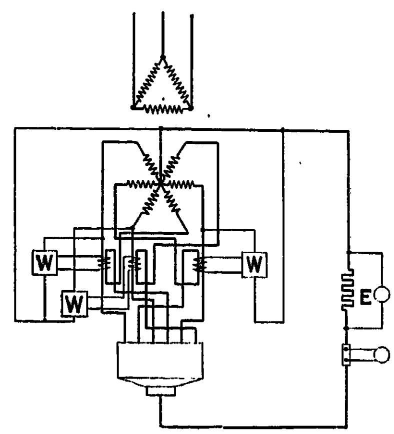

FIG. 2—MEASUREMENT OF RECTIFIER LOSSES—DIAGRAM OF CONNECTIONS

The wattmeter voltage coil is connected to one of these anodes and ground. The wattmeter thus measures the output of two opposite phases of the transformer, and the current transformer, alternately receiving positive and negative current impulses, is no longer saturated so that accurate measurements can be made. A diagram of connections is shown on Fig. 2. By this method half of the secondary copper losses of the transformer are included in the measurement, but the readings can be corrected accordingly.

In the manufacture of rectifiers, load tests are more essential than in the manufacture of other electrical equipment, as there are no other ways for predetermining the performance of rectifiers under load, and for checking whether their construction has been conducted with the requisite care. For a load test at normal voltage and normal output, the rectifier is fed by a transformer having the same rating. In the last few years, due to the rapid increase in capacity of rectifiers, a test at full load or overload, run simultaneously on several

*Mercury Arc Power Rectifiers, by Marti and Winograd, McGraw-Hill, Chapter XII.

rectifiers, will tie up an excessive amount of testing equipment. The capacity of the required transformers can, however, be reduced almost one-half by the following ingenious method:

As shown in Fig. 3, half of the anodes of the rectifier are fed at normal voltage and normal current by a transformer which therefore must have only half the capacity of the rectifier. The d-c. output is fed back into the a-c. line by a motor generator, also having half the rating of the rectifier. The remaining anodes of the rectifier are fed at a fraction of the normal voltage and at normal current by another transformer which has, therefore, only a very small rating and whose output is usually dissipated in a water rheostat. This method is made possible by the fact that the voltage drop in the rectifier is independent of the voltage on the load, so that both groups of anodes can work in parallel without difficulty. All anodes are fully loaded and, with half of them receiving the full voltage, the operating conditions are practically the same as when all anodes are fed at normal voltage. When the test has run for half the required time, the connections between the groups of anodes and the two transformers are interchanged so that each group of anodes will have received full voltage during one-half of the run.

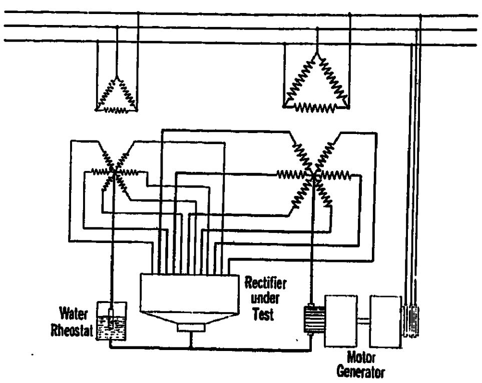

FIG. 3—LOAD TEST OF RECTIFIER—DIAGRAM OF CONNECTIONS

STANDARDIZATION OF RECTIFIERS

Fig. 4 shows schematic cross-sections on a comparative scale of one series of rectifiers of the Brown Boveri design having respectively, 6, 12, 18, and 24 anodes. It may be seen that the general outline of all types is the same; this basic construction was adopted over 15 years ago and has proved satisfactory ever since without any major changes. Each rectifier comprises a water-jacketed cylinder covered by an anode plate which carries a condensing dome. The anodes are carried by the plate, from which they are insulated. The capacity of the rectifier determines the number of anodes required, which in turn determines the dimensions of the anode plate. The anodes are sealed in their insulators by means of mercury seals provided with gages giving a permanent check of the condition of the seals. In order that the cathode may easily be removed without lifting the cylinder, the latter is provided with feet of adequate height. Each welding seam of the working cylinder is covered by a channel welded on the cylinder so that, by putting the channel under air pressure, it is possible to test each seam separately without closing and evacuating the whole cylinder.

The types of rectifiers shown on Fig. 4 are standard and, in their design, care was taken to use as many identical parts as possible so as to reduce the number of spare parts necessary for different sizes. Among those parts are the anodes, the anode insulators, ignition anodes, excitation anodes, cathode plates, and the component parts of the seals for their various joints.

The evacuating equipment, which consists of a rotary pump and a high vacuum pump, is the same for all types of rectifiers, two sets of pumps in parallel being used for the larger types of cylinders. In order to simplify erection and reduce the space required for the rectifier, the pumps are now mounted directly on the cylinder.

The excitation and ignition transformers are combined in one compact unit which is the same for all sizes of rectifiers.

EXPANSION OF FIELDS OF APPLICATION OF MERCURY ARC RECTIFIERS

The majority of high-capacity rectifiers put in service recently are used for traction purposes, for which the experience of a number of years has shown that they are especially suitable. Advantage has often been taken of the possibility of connecting a 25-cycle rectifier set to either a 25-cycle or a 60-cycle supply, as necessary in some installations, or switching it from one supply to the other, should either supply fail. Several rectifiers operating in parallel can also be fed from different a-c. sources, and even from sources of different frequencies, without any of the difficulties encountered with other converting equipment.

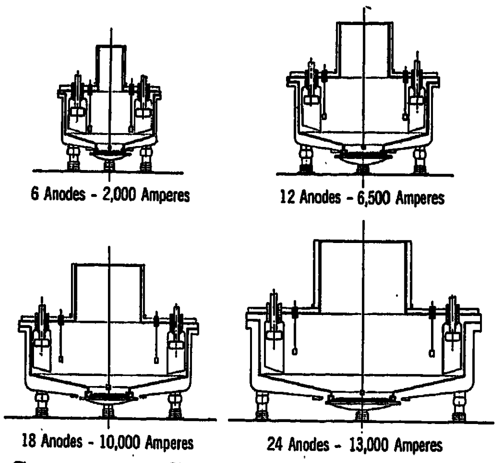

FIG. 4—COMPARATIVE CROSS-SECTIONS OF A SERIES OF BROWN BOVERI RECTIFIERS

A new field of application for large-capacity mercury arc rectifiers was opened with the putting in operation early in 1930 of two 2500-kw., 650-volt, nominally rated rectifiers in a substation supplying power to the Philadelphia City Transit subways. The installation is shown in Fig. 5 and, as can be seen, space has been provided for two additional units. The load conditions which have to be met in this kind of service are best illustrated in the portion of a load chart shown in

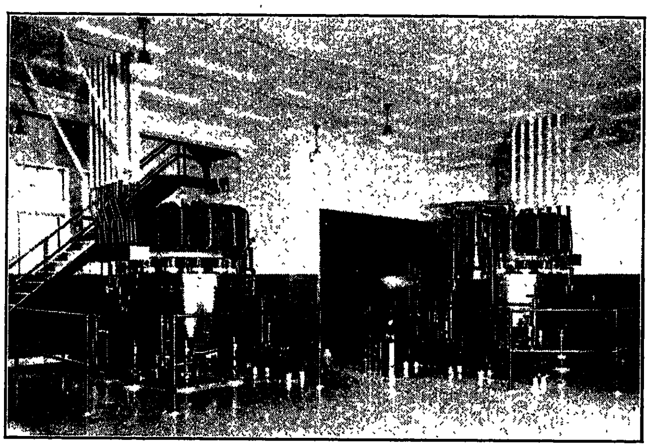

FIG. 5—VIEW OF TWO, 2500-KW., 630-VOLT NOMINALLY RATED RECTIFIERS IN SUBSTATION OF PHILADELPHIA CITY TRANSIT DEPARTMENT

Fig. 6. This shows the suddenness with which peak loads are imposed on the converting equipment supplying rapid transit systems. In this installation the voltage rise at no load is suppressed in the manner explained previously, under the heading Engineering Developments.

The mercury arc rectifier has a most promising application in railway portable substations. Fig. 7 shows such a substation for 600-kw., 575 volts in use on the

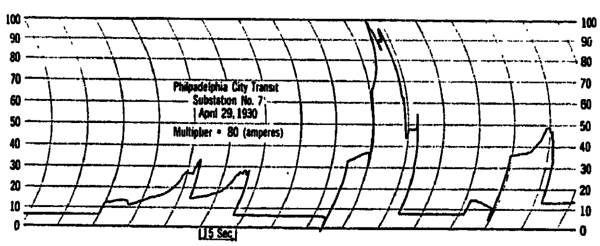

FIG. 6—PORTION OF LOAD CHART OF RECTIFIERS SHOWN IN FIG. 5

Calgary Street Railway system. In this substation, the rectifier and auxiliaries, together with switching equipment, are protected by housings, whereas the transformer and reactor are left outdoors. Portable substations being mounted on springs, the capacity of rotating equipment which could be installed in them is very limited as machines of large capacity would produce excessive vibration in a car of standard design. The mercury arc rectifier, on the other hand, being a static piece of apparatus, the only limitations to its use will be the weight and the size of the transformer. It is comparatively easy to install a complete rectifier substation for 3000 kw. at a d-c. voltage of 600, 1500 or 3000 volts on a standard flat car, which is far beyond the present requirements for portable substations. The mercury arc rectifier is specially desirable for this application in view of the ease with which it can be remote-controlled or made fully automatic.

The limitations of rotating equipment have retarded the development of portable substations, but with rectifiers the advantages become so numerous that it may be predicted that their use will be very extensive in the future. Portable substations can be erected complete on the manufacturer's premises and delivered ready to be connected to the line, therefore doing away with all erection expenses. In case of a failure of the equipment, the complete substation can be hauled into the car barn where all repair facilities can be concentrated so that

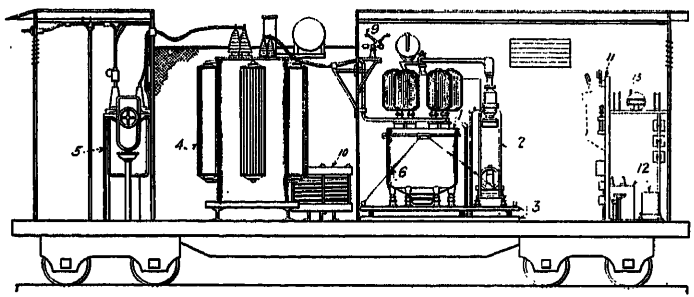

FIG. 7—ELEVATION OF 600-KW., 575-VOLT AUTOMATIC PORTABLE RECTIFIER SUBSTATION OF CITY OF CALGARY

1. Rectifier cylinder
2. Vacuum pump
3. Frame for rectifier and vacuum pump
4. Transformer
5. Oil circuit breaker
6. Guy wires for rectifier cylinder
9. Lightning arresters
10. Air-core reactor for filter equipment
11. Switchboard
12. Ignition-excitation set
13. Filter equipment
14. Protective rail

repairs can be made rapidly and economically. The portable railway substation therefore presents a number of advantages over the stationary type and it may not be impossible that some day they will completely supersede the latter, at least for street railway service and especially for electric trackless trolley buses where the lines could be re-routed with no further expense than that necessary for removing and re-erecting the trolley wires.

For installations with very large d-c. outputs, it may be economical to install the rectifiers outdoors, and, as may be seen from Fig. 8, rectifiers lend themselves readily to very compact layouts. The cylinders are covered by sheet metal housings, and are directly connected to their transformers. Rectifiers and transformers can be rolled into position on a car running on adjacent track siding. The d-c. feeders can be brought out overhead or through cables from the switch house

located in the center of the substation. The a-c. feeder layout is in accordance with standard practise, and requires no further explanation.

A very interesting application of high-voltage rectifiers was found in radio transmitting stations, where

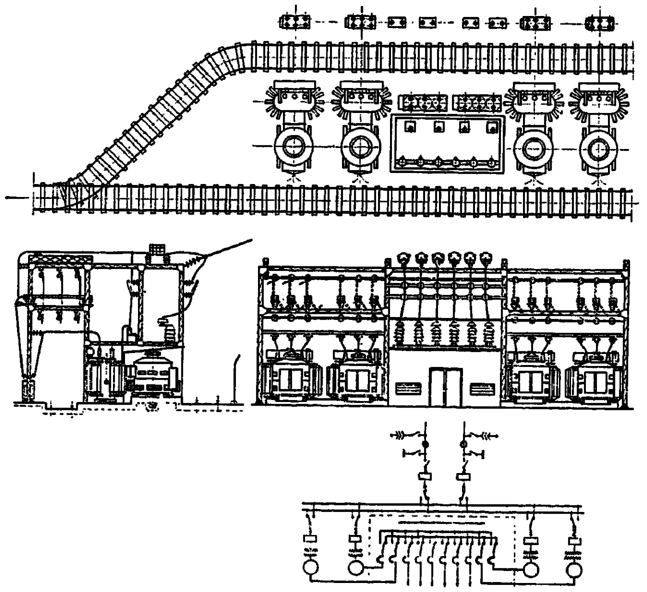

FIG. 8—PROJECT OF LAYOUT OF OUTDOOR RECTIFIER SUBSTATION

voltages ranging from 10,000 to 30,000 volts are required. For such stations of considerable power, the mercury arc rectifier is especially well adapted as it can be put in service instantly, resists short-circuits which

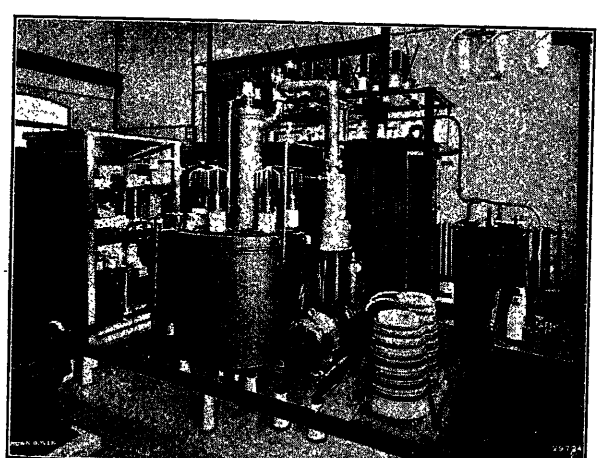

FIG. 9—VIEW OF 400-KW., 13,000-VOLT RECTIFIER FOR MARCONI WIRELESS TELEGRAPH CO., LTD.

are disastrous to other types of converters and has a high efficiency which will effect a considerable saving compared to thermionic tubes. In addition, the life of the rectifier is indefinite, whereas the tubes have a limited life. Fig. 9 shows a 400-kw., 13,000-volt rectifier installed by the Marconi Wireless Telegraph Company, Ltd., at Chelmsford, England. It can be seen in this figure that the anodes are equipped with over-size insulators; furthermore, that the cooling water is supplied through long rubber hoses wound on insulators shown in the foreground, in order to prevent excessive leakage currents to ground. Another unit, of 270 kw., will shortly be installed by the same company at Lucerne, Switzerland. This application was described because it shows that mercury arc rectifiers can, without difficulty, be built for heavy currents and high d-c. voltages.

Considerable interest was aroused by the installation of six rectifiers for 5,000 amperes each at 460-560 volts by the Consolidated Mining & Smelting Company, Trail, B. C., as shown in Fig. 10. These rectifiers are used for electrolytically refining zinc and are the largest installed on the American continent. In this type of installation, the load is constituted mainly by the

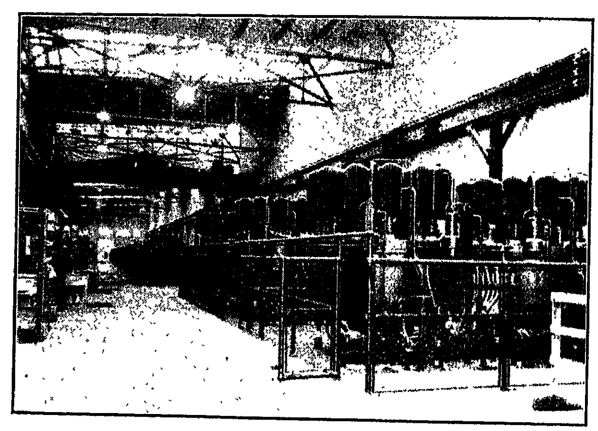

FIG. 10—RECTIFIER INSTALLATION OF SIX, 5000-AMPERES, 460/560-VOLT RECTIFIERS FOR CONSOLIDATED MINING & SMELTING CO., TRAIL, B. C., CANADA

counter-e. m. f. of the cells, which have only a small amount of resistance. It is easy to compute that, with this type of load, the alternating current due to the voltage ripple will be much larger than with resistance of inductive loads, but a very small amount of inductance in the d-c. circuit is sufficient to reduce the ripple current to any desired value.

In hydrogen plants, one advantage of the rectifier is that it is not subject to reversals of polarity, which are a source of disastrous explosions. Moreover, in the case of large electro-chemical installations operating continuously 24 hr. a day, the absence of brush wear alone constitutes an appreciable advantage for the steel-enclosed mercury arc rectifiers.

Very recently a number of rectifiers has been installed for supplying power alternately to a 250-volt, 3-wire, d-c. Edison system and a 600-volt railway system. As the mercury arc rectifiers work at any commercial voltage these abnormal operating conditions

are being taken care of by merely changing the transformer connections.

Conclusion

This brief study of recent rectifier developments shows that the rectifier can be used to advantage for any power application requiring conversion from alternating to direct current. It has made available for existing applications reliable units of higher capacity and has permitted the development of applications hitherto retarded by the lack of a suitable converter. Due to the ease of its generation and conversion, alternating current has taken a long lead over direct current, and is being used for applications where direct current would be preferable. Since the advent of the rectifier, however, the use of direct current has received a considerable impetus, and it will no doubt gain additional momentum in the near future.

Discussion

S. Withington; Mr. Marti's paper constitutes an appropriate addition to the literature of experience and description which is accumulating in connection with the mercury arc rectifier.

One of the more important fields for which rectifiers or converters are required is in electric traction. It is of interest to note that of the two examples of 3,000-volt d-c. steam railroad electrification which have been placed in operation during the present summer, one is equipped entirely with motor-generators and the other entirely with static rectifiers. The relative performance of these two types of equipment will be observed with a great deal of interest, as the duties are nearly identical and the inauguration of operation practically contemporaneous.

The subject of rating of mercury arc rectifiers should be settled as soon as possible. The characteristics of rectifiers are in some respects fundamentally different from those of rotary converters or motor-generator sets, and it is not logical to base the rating upon such types of electrical apparatus. It is to be hoped that the joint committee which has undertaken the standardization of mercury arc rectifier ratings will arrive at an early conclusion and that this conclusion will be based upon actual characteristics and not upon analogy.

One of the advantages of static rectifier equipment as compared with rotary converters or motor-generators which Mr. Marti might well have mentioned is in the restoration of service in the event of an interruption to the source of power. In the case of the rectifier the d-c. power may be completely restored simultaneously with the restoration of the supply, while with rotating equipment the entire requisite machine capacity must be started and connected to the supply before the d-c. load can be carried. This difference may be of considerable importance in the case of comprehensive d-c. networks. Some further discussion of this would be of interest.

Mr. Marti has called attention to the adaptability of rectifiers as compared with rotary apparatus for portable substations. There is one limitation which may be important under certain circumstances, unless proper provisions are made. A supply of cooling water is not always available at a location (especially a temporary one) which may be convenient, even though the water cooling system may be a closed one.

The reference which Mr. Marti made to outdoor application of rectifiers is significant. The tendency towards adaptation for outdoor installation of all sorts of electrical apparatus is evident and the saving thus made possible is obvious. The chief difficulty is maintenance in inclement weather. It would seem that this can be overcome by proper temporary shelter.

Development of a Relay Protective System
On the Lines of the Southern California Edison Company, Ltd.

BY E. R. STAUFFACHER[1]

Member, A. I. E. E.

Synopsis.—A record of the application of protective relays on the system of the Southern California Edison Company, Ltd., is presented. The history of this development of the protective relays in the 220-kv. transmission line, together with the results of the application of protective relays is recorded. In view of the limited application of carrier current protection, considerable discussion is presented covering its application on a section of the 220-kv. transmission system. Allied considerations pertaining to system stability on the 220-kv. system are discussed, and the rearrangement of the 66-kv. system as a means of improving system stability is also presented. In the interest of improving service, certain changes on the lower voltage 16-kv. and 11-kv. systems have been made.

INTRODUCTION

THE last decade has witnessed notable developments in steam generating units, the extension of high-voltage transmission together with the application of increased sizes of transformers, oil circuit breakers and synchronous condensers. The plans for the operation of extended high-voltage transmission networks have become a reality and the reliability of transmission over long distances now compares favorably with the reliability of transmission over much shorter distances a few years ago. The development and application of protective relays has made it possible to maintain continuity of service under conditions which would have been impossible ten years ago. In addition to providing uninterrupted service, protective relays permit a more efficient use of transmission lines by utilizing several lines in parallel with a consequent reduction in $I^2 R$ losses even though one line might be of sufficient capacity to handle the load.

The serious application of protective relays to the system of the Southern California Edison Company, Ltd., dates from approximately ten years ago. In 1920 a program of installing modern type induction relays was inaugurated on the 66-kv. lines. A few years later when the Big Creek 150-kv. lines were modified for 220-kv. operation protective relays were installed although these lines up to this time had been operated without automatic devices of this nature. Since this time the use of modern induction type relays has extended throughout the system with the exception of the 2.3-kv. and 4-kv. lines which only require plunger type relays. At present there are in use approximately 9,300 protective relays on the system.

PREVIOUS WORK

In 1923 the Big Creek transmission system was changed from 150-kv. to 220-kv. operation. Previous to that time no protective relays for automatically isolating defective sections of the lines had been used. The practise up to 1923 had been to lower the voltage on the transmission lines manually by introducing resistance in the fields of the various generators and synchronous condensers. By means of a "trouble" rheostat the operators throughout the transmission system lowered the voltage until the arc broke, and when ground currents ceased to flow, the voltage was restored to normal by hand. This served to remove the short circuit from the system, but necessarily resulted in a service interruption. At the time the lines were changed to 220-kv. operation it was realized that this system of removing short circuits could no longer be tolerated, and the decision was made to install protective relays. The transmission system at that time consisted of only two lines from the Big Creek group of generating plants to the Eagle Rock and Laguna Bell terminal substations, with a substation known as Vestal and a switching station known as Magunden located in the San Joaquin Valley and approximately in the middle portion of the transmission system. Induction type current balanced relays were relied upon for the automatic isolation of faults. The connections were made so that two lines at a given generating plant or substation were balanced against each other and under automatic protection, but if it was necessary to remove one line from service the remaining line was made solid or non-automatic. Phase relays only were installed. Provision was made at the generating plants and substations to automatically insert resistance in the field of each of the machines in service and thus lower the voltage if by chance a fault should occur on a section where only one line, that is, the line which was not provided with protective relays, was in service in a given section. This scheme of relay protection was a great improvement over the past non-automatic scheme, but a few years' service showed that there were certain improvements which could be made to advantage.

The first change was the addition of current balanced residual or ground relays similar to the phase relays already installed, but designed to operate at a lower value of current. This modification improved the relay operation considerably as it speeded up operation at the time of the heavier ground fault currents and eliminated a faulty section of line when a comparatively light ground current would flow. Under the previous

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conditions of using phase relays only there would not have been sufficient current to cause the phase relays to operate. With this relay set-up the larger percentage of faults was cleared without interruption to service. However, a few of the short circuits were either slow in clearing or occurred at the time of a heavy load on the system, resulting in the two ends of the system going out of step even after proper elimination of the faulty section of the transmission line.

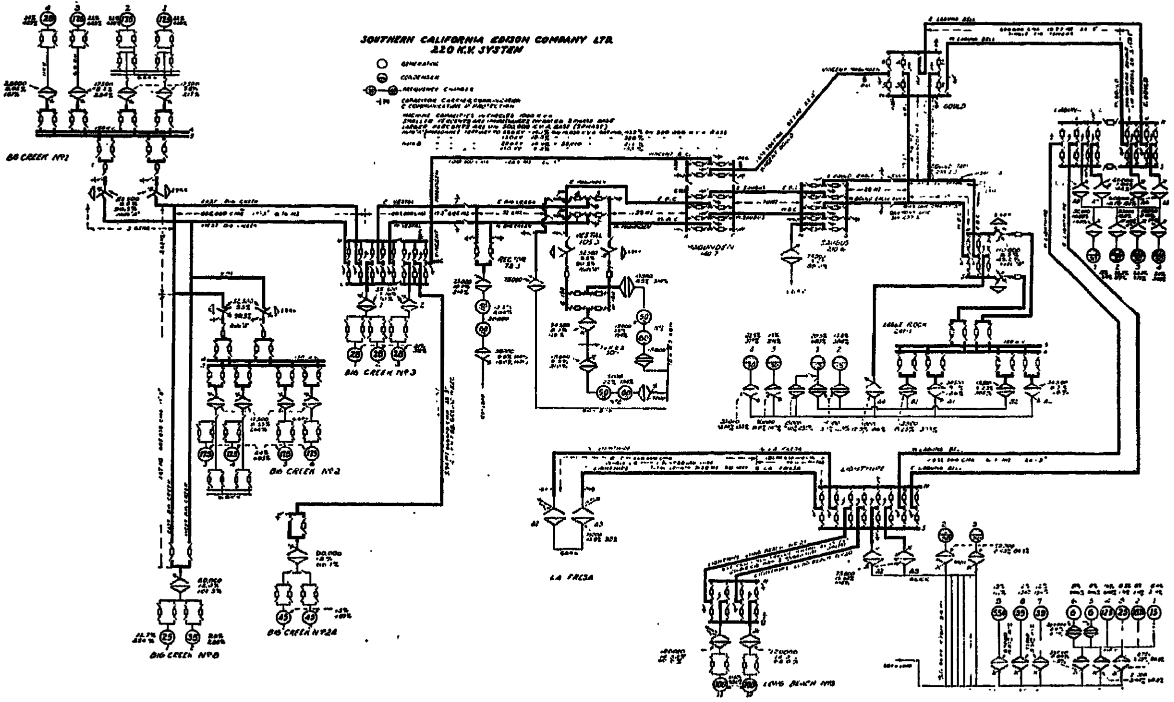

FIG. 1—SINGLE-LINE DIAGRAM SHOWING THE 220-KV. TRANSMISSION SYSTEM OF THE SOUTHERN CALIFORNIA EDISON CO., LTD.

In 1925 arrangements were made with the Westinghouse Company to install special recording instruments on the transmission system. The results of the first eighteen months of investigation have been published already[2] and need not be repeated here. Since 1927 there has been a considerable extension of the 220-kv. transmission system. The development of the protective relay system and the results of its use will be recorded in this paper.

The present 220-kv. system extends from the hydro plants in the Big Creek territory to the steam generating plant at Long Beach—a distance of about 280 miles. Fig. 1 is a single line diagram of this system showing the connections and relation of the various generating plants and substations. Table I presents the synchronous capacity of the rotating equipment at the various generating plants and substations.

220-KV. RECORDS OF FAULTS

A careful record of the flashovers and other causes which might cause interruptions together with the protective relay operations has been kept from the beginning of the period of automatic elimination of faults on the 220-kv. transmission system. Table II gives this information up to the present time. In this table will be noted the number of transmission faults and the faults cleared correctly together with the number of times the protective relays were not able to clear faults. The relay scheme during the past was such that the removal of one line of a section for maintenance left the remaining line non-automatic. Consequently a fault on this remaining line could not be cleared except by lowering the transmission line voltage with a resulting interruption to service. Another situation was soon apparent. With only two 220-kv. transmission lines available and with the generating stations located at one end of the system and the load at the other, as was the case up to a few years ago, instability would often result at the time of heavy loads even though the relays

TABLE I

Name of station	Number of units	Total capacity name plate rating
Generators		
Big Creek No. 1 hydro generating plant...	4	80,500 kv-a.
Big Creek No. 2 hydro generating plant...	4	70,000 "
Big Creek No. 2A hydro generating plant..	2	90,000 "
Big Creek No. 3 hydro generating plant...	3	84,000 "
Big Creek No 8 hydro generating plant...	2	60,000 "
Long Beach No. 3 steam plant...........	2	200,000 "
Synchronous Condensers		
Eagle Rock substation..................	4	90,000 kv-a.
Laguna Bell substation.................	4	140,000 "
Lightipe substation....................	2	100,000 "
50-60 Cycle Frequency Changers		
Rector.................................	1	30,000 kv-a.
Vestal.................................	2	30,000 "

Total synchronous capacity—974,500 kv-a.

2. *Transients Due to Short Circuits*, by Wood, Hunt and Griscom, A. I. E. E. TRANS., Vol. 47, p. 68.

operated correctly to clear a fault. This situation led to the installation of oscillographs and curve drawing instruments at a number of the generating plants and substations so that the transient conditions resulting from a fault could be recorded. A study of these records indicated the necessity for clearing the faults in a shorter time, limiting the ground current to as small a value as practicable, quick response of generator field excitation, and for an additional transmission line.

TABLE II
220-KV. INTERRUPTIONS

Year	Number of faults	Faults cleared correctly	Number of times relays not in at time of fault	*System interruptions	Percentage system interruptions to faults
1924	22	8	13	14	63.8
1925	25	19	4	3	12
1926	36	27	1	8	22.2
1927	24	13	4	9	37.5
1928	26	18	5	7	27
1929	30	25	0	2	6.7
1930 Through June	20	18	0	0	0

*Due to load, severity of trouble, speed of clearance of trouble, location of trouble, system connections which determine source of power, and to protective relays being out of service.

The recording instruments have since been installed as permanent equipment. In addition a number of Hall high-speed recorders is in service at the Big Creek hydro plants and substations to measure fault current to ground and voltage dips at the time of the fault. At Long Beach Steam No. 3 a nine element Westinghouse oscillograph together with a standard 50-cycle tuning fork is permanently installed to record transient disturbances.

Protective Relay Installations

The records which have been kept of the flash-overs and other troubles on the 220-kv. transmission system show that at no time has there been any transient fault which has not been accompanied by a flow of some ground current. The wide spacing of the conductors at this high voltage no doubt is responsible for the fact that the likelihood of phase-to-phase faults without a fault current to ground is rather remote. As a result of this situation, the practise of the past few years has been to abandon the use of phase relays entirely, and to depend upon ground or residual relays only for protection. Where two or more lines are connected to a generating plant or substation, these lines are protected by induction type current balanced relays connected in the residual connection of the bushing type current transformers mounted in the high-tension oil circuit breakers. The relay scheme for single-line operation was changed so that protection was provided for a single line by means of residual directional relays actuated from the residual connection of the current transformers in the oil circuit breakers and from current transformers connected in the neutral or the residual connection of the station transformers. The limitations of installation of the neutral or ground end of the 220-kv. transformers necessitated that current transformers be connected in each of the single-phase units, making up a three-phase bank and the residual connection from these current transformers in place of the usual method of using one current transformer connected in the neutral of a bank of three transformers, as is generally the case when lower voltage transformers are under consideration.

The question of testing protective relays on important transmission lines is always a problem. To make an over-all test of the relays with the oil circuit breaker necessitates that a line be removed from service or the line made non-automatic during the test, and the chance must be taken that no trouble occurs on the transmission line at the time a test is being made. Generally it works out that the line may be made non-automatic and the relays tested without any trouble, but there have been a few cases when trouble did occur when a section of line was non-automatic at the time of testing relays, and as a result it was decided to eliminate the possibility of a transmission line interruption from this source by installing duplicate sets of residual relays for each line. This amounts to having one set of relays for each of the two oil circuit breakers controlling a transmission line. This permits the testing of one set of relays with its oil circuit breaker and leaving the line under adequate protection with the remaining set of relays, with this particular oil circuit breaker controlling the line which is being tested.

This latest scheme of protection has been installed throughout the full length of the 220-kv. transmission system, and was only completed in 1930. The two sets of relays are designated as set *A* and set *B* at the various generating plants and substations. The connections to the relays are such that normally, with all lines in, dependence is placed upon current balanced residual relays. For single-line protection residual directional current relays or simple over-current relays are used. By means of the type JD relay, which is an accurate disk type of d-c. timing relay or the type PQ-26 relay which is a plunger type, provision is made to assure operation of only the oil circuit breakers on the line in trouble at the time of a fault. This is accomplished by utilizing the timing relay to introduce a few seconds interval of time between the opening of the oil circuit breakers on the line in trouble, and the making of the remaining line automatic for single-line protection.

The 220-kv. Vincent line from Gould substation to Magunden substation, and from Magunden substation to Power House Big Creek No. 3, has slightly different characteristics from the two original Big Creek lines and does not connect with all of the substations between Big Creek No. 3 and Gould, as is the case with the two original lines. As a result, the Vincent line has a somewhat different current distribution than the two other lines at the time of fault on certain portions of the system, and it has always been somewhat of a problem to provide it with proper protection when depending upon

current balanced relays which were satisfactory for the two original lines. The two terminals of one of the two sections of this line are connected to switching stations which are not provided with any means of obtaining potential from the 220-kv. transmission line, and for this reason it was not possible to provide protection with power directional relays. As a result of this condition, it was decided to investigate the possibilities of utilizing the carrier current pilot protection scheme of protection originally described by Fitzgerald,[3] and which offered certain advantages not readily obtainable with other forms of protection on high voltage and long sections of a transmission line.

The carrier current pilot scheme of protection has been in service for approximately a year on the Gould-Magunden section of the 220-kv. Vincent transmission line. It is similar to the other forms of protection on the 220-kv. system in that it provides for line-to-ground short circuit protection only. It may be compared to the pilot wire relay circuit where the pilot circuit is completed by means of a physical conductor between the two stations at the end of the transmission line section. The same net results are obtained, but the exchange of relay operating current does not occur with the carrier current system of pilot protection. It operates in such a manner as to compare the direction of the instantaneous residual currents at the two ends of the section of line affected. If the instantaneous residual current is in phase, that is, in the same direction, indicating that a fault is external to the section protected by the carrier current pilot protection, the equipment operates to lock out and prevent the induction type over-current relays from tripping the automatic oil circuit breakers. However, if the fault is in the section of line under carrier current pilot protection, current will flow towards the fault from the energy sources at each end of the section and the currents at the two ends will be approximately 180 deg. out of phase with each other. Under these conditions of the instantaneous residual currents flowing in opposite directions, a fault within this section is indicated and the carrier current receiver at each end is made inoperative automatically, which permits the induction type over-current relays to function at both ends and trip the oil circuit breakers, thus clearing the fault in this section from the system. A detailed description of this installation has been published elsewhere,[4] so it will not be necessary to repeat it here. Table III gives the results obtained with this protective equipment. When it is considered that it is an innovation in protective schemes, and that a great many problems had to be worked out before it was manufactured and installed the results have been quite satisfactory. At each of the two switching stations the section of the 220-kv. line which is protected terminates in a set of two oil circuit breakers which connect to the two high-voltage buses at each station. Coupling between the 220-kv. Vincent transmission line and the carrier current pilot protection is obtained by means of oil-filled coupling capacitors connected to two of the three-phase wires,

TABLE III

OPERATION OF CARRIER CURRENT PILOT PROTECTION ON THE VINCENT 220-KV. LINE—95 MILE—MAGUNDEN TO GOULD SECTION

Date	Location of fault	Operation of carrier current pilot protection	Remarks
July 3, 1929	Exterior to section	Incorrect	Insulator string parted, grounding conductor. Oil circuit breaker at Gould tripped out on Vincent Line as the result of incorrect current transformer connection at Gould
July 3, 1929	Exterior to section	Incorrect	Same trouble as above. Switch opened at Magunden when defective line accidentally energized
Aug. 9, 1929	Exterior to section	Correct	Tree blown into line
Aug. 13, 1929	Within section	Correct	Lightning
Aug. 14, 1929	Exterior to section	Correct	Station 220-kv. transformer breakdown
Aug. 19, 1929	Exterior to section	Correct	Brush fire under line
Aug. 20, 1929	Exterior to section	Correct	Brush fire under line
Aug. 25, 1929	Exterior to section	Correct	Breakdown of 220-kv. oil circuit breaker
Oct. 27, 1929	Exterior to section	Correct	Bird trouble on line
Nov. 17, 1929	Exterior to section	Correct	Bird trouble on line
Dec. 25, 1929	Exterior to section	Correct	Bird trouble on line
Dec. 31, 1929	Exterior to section	Correct	Wire thrown over 220-kv. line
Jan. 7, 1930	Exterior to section	Correct	Unknown—heavy wind at time of trouble
Jan. 13, 1930	Exterior to section	Correct	Bird trouble on line
Feb. 1, 1930	Exterior to section	Correct	Bird trouble on line
March 14, 1930	Within section	Correct	Sleet storm along line
March 14, 1930	Exterior to section	Correct	Overhead ground wire parted.—Storming
March 14, 1930	Within section	Correct	Sleet storm along line
March 14, 1930	Within section	Correct	Sleet storm along line
March 14, 1930	Within section	Correct	Sleet storm along line
March 14, 1930	Within section	Correct	Sleet storm along line
March 14, 1930	Within section	Correct	Sleet storm along line
March 15, 1930	Within section	Correct	Sleet storm along line (The eight cases of trouble above were evidently caused by sleet loading the conductors and the overhead ground wires resulting in contact between them)
March 25, 1930	Exterior to section	Correct	Wire in contact with conductors
April 13, 1930	Exterior to section	Correct	Flashover on bushings of 220-kv. station transformer
April 16, 1930	Exterior to section	Correct	Bird trouble on line
April 23, 1930	Exterior to section	Correct	220-kv. oil circuit breaker trouble, flashing to ground
April 23, 1930	Exterior to section	Correct	Bird trouble on line

SUMMARY

Total cases of trouble since carrier current pilot protection installed	28
Cases of trouble exterior to section	20
Cases of trouble within section	8
Correct operations	26
Incorrect operations	2

3. *A Carrier-Current Pilot System of Transmission Line Protection*, by A. S. Fitzgerald, A. I. E. E. TRANS., Vol. 47, p. 22.

4. "Carrier Current Replaces Relay Pilot Wire," E. R. Stauffacher and F. B. Doolittle, *Electrical World*, Vol. 95, No. 12, p. 580.

each connected from line to ground, which gives what is termed "interphase" coupling. This coupling is made to the same phase wires at each end of the section protected, and the same set of capacitors is utilized for transmission of the carrier current pilot protection carrier frequency and the carrier current telephone system carrier frequency over the same transmission line. Between the coupling capacitors and the 220-kv. oil circuit breakers at each station are installed carrier current frequency traps built quite similar to a large choke coil and having a capacity of 800 amperes continuous duty, and an inductance of approximately 70 microhenrys. Due to the double use of the capacitors, it is necessary to filter the protection carrier frequency and the communication carrier frequency into their proper channels.

The relatively heavy volt-ampere burden placed on the bushing type current transformers by the carrier equipment and the necessity of exciting the carrier current equipment from the secondaries of these bushing type current transformers requires that the fault current to operate the equipment must be 320 amperes or more. This rather coarse setting of 320 amperes has been satisfactory, but it would be desirable to obtain a setting of from 200 to 250 amperes if practicable. Studies and experiments are now under way by the manufacturers which give promise of obtaining certain characteristics which will permit the lower setting to be used. The over-current induction type relay which is used is so designed as to operate at an unusually high speed for this type of relay. In order to obtain the greatest speed of operation of the carrier current pilot protection consistent with a reasonable life of the vacuum tubes, the filaments of all of the tubes are operated at approximately full voltage, but with no excitation on the plates. The experience so far indicates that it is necessary to make a transmission check of the equipment at frequent intervals, and provision has been made to make a simple transmission check at each station every two weeks. This check requires about one hour to make, and has been simplified so that it is now a part of the regular duties of the station crew in each station.

Allied Considerations

The successful application of protective relays on a transmission system is so closely linked with the static and transient stability of the system that consideration must be given to these features whenever relays are considered.[5] Stability is the outstanding feature of long high-voltage transmission lines which determines the amount of power which can be commercially handled, and it is obvious that the stability of a transmission system is determined by the longest section of line which may be suddenly isolated from the system to clear a fault. The static stability limit can be readily calculated so that it is known that if the power demand is such that the reduced transmission line capacity will not hold the generating and receiving ends of the line in synchronism, instability will result. The determination of the transient stability limit does not readily permit a definite solution as the factors to be considered cannot always be obtained with the accuracy which is desirable. However, there is a number of outstanding features which can be considered and applied to a transmission system which will help greatly in maintaining stability under conditions of heavy short-circuit currents.

First, a prompt clearance of a fault from the system is without a doubt the most important consideration. It is agreed now that the main factor in reducing disturbance and preventing loss of synchronism between the generating and receiving ends of a transmission line is the rapidity of operation of protective relays and oil circuit breakers. During the past few years a great deal has been accomplished along these lines. Protective relays are now available which will operate in a few cycles, and the manufacturers can now supply oil circuit breakers guaranteed to operate in periods of between eight and twelve cycles. Unfortunately such equipment has not been available for any great length of time, and the cost of replacing or rebuilding present 220-kv. oil circuit breakers is so high that it is not justified except as a last resort. On the system of the Southern California Edison Company, Ltd., the recent oil circuit breakers purchased have been of the modern high-speed type, and all future oil circuit breakers no doubt will take advantage of this feature of protection to gain greater assurance of stability under times of system disturbance.

Second, the opinion still holds that the design of generators and synchronous condensers from the standpoint of short-circuit ratio is important. A high short-circuit ratio, somewhere between 1.5 to 2, is quite desirable as it results in certain characteristics of machines which tend to increase the system stability. The generators which have been installed at Big Creek and Long Beach Steam Plants during the past five years have been designed with as high a short circuit ratio as practicable so as to take advantage of this feature of maintaining system stability.

Third, quick response or super-excitation provided for the purpose of building up a voltage quickly across the field winding of a synchronous machine by providing additional magneto-motor force to neutralize the demagnetizing action of the short-circuit current in the armature winding, is not considered quite as important now in relation to other features of system stability as it was a few years ago. However, it is felt that if this quick response excitation can be applied at the time the newer and larger generators are installed, and to certain of the older and larger sized generators, that it is justified and assists materially in maintaining transient stability.

Fourth, on the system of the Southern California Edison Company, Ltd., experience has shown that in the

5. "Extra High Voltage Transmission with Special Reference to American Practice," J. P. Jollyman and E. R. Stauffacher, World Power Conference, Tokyo, 1929, Paper No. 453.

case of transmission line troubles on high-voltage lines, faults from phase to ground predominate, and due to the construction of 220-kv. transmission lines, this is probably the case with most systems. The power consumed in the fault causes a heavy power demand upon the transmission system as a result of the flow of ground current. Accordingly, it has been decided to take steps to limit the flow of ground current and the latest transformer banks connected to the 220-kv. system in the metropolitan area adjacent to Los Angeles have been designed to operate with some device in the neutral to limit the flow of current. At La Fresa Substation, current limiting reactors rated at 600 amperes—60,000 volts—50 cycle have been installed. A reactor is installed in the neutral of each of the two 75,000-kv-a., 220-kv. star to 66-kv. delta transformer banks and the transformers are so designed that the 220-kv. neutral end is provided with 73-kv. insulation. Around each of the reactors from terminal to ground is mounted a sphere-gap set to flash over at 100 kv. The reactors are enclosed in a tank and oil immersed. The 120,000-kv-a., 16-kv. delta to 220-kv. Y transformer bank recently installed at Long Beach Steam Plant No. 3 is designed with 73-kv. neutral insulation and operates with a neutral grounding device designed for use with a non-resonating transformer and rated at 4 amperes, 50 cycles, 73,000 volts. These devices for limiting the ground current have been in service for several months, and so far have performed satisfactorily. They are considered the first step in the program of limiting the flow of ground current on the 220-kv. system, and no doubt will be used further as other transformer banks are installed.

Fifth, by means of momentarily decreasing the output of the generators at the sending end of a long transmission line at the time of a fault, it appears that the tendency for the generators to get out of step with the load at the receiving end could be decreased considerably as the result of reducing the load which is being transmitted. A device which will be actuated by ground current and which will operate upon the governors of the water wheels at the generating plants is under consideration. Generators at the steam plant adjacent to the receiving end should be able to pick up momentarily the greater portion of the load which is dropped, and as a result the system frequency should not suffer to any extent.

Sixth, in applying transient stability calculations, the characteristics of the generators, synchronous condensers, transformers and lines can be determined, but there is little information available covering the characteristics of a mixed load of a large city. There is need for further knowledge concerning the stability characteristics of a load supplied by a transmission system. The combination of industrial and railway power, together with lighting and heating service, and the question as to how much such a load affects the power system at the time of a fault on the transmission line, is one which deserves considerable study, and when the information is available concerning it, should assist materially in making transmission line stability calculations.

Seventh, it is apparent that the ground impedance of transmission lines at the time of faults along the line is a factor which must be considered carefully at the time of studying relays or predicting inductive interference phenomena, and the available knowledge concerning this ground impedance throughout various portions of the country is not sufficient. To gather more information concerning this, a few tests have been made on the system of the Southern California Edison Company, Ltd.,—the latest being made on the Lighthipe-La Fresa 220-kv. lines. It was found that the measured zero phase sequence reactance per phase of the Lighthipe-La Fresa 220-kv. lines when considering one line alone amounted to 1.64 ohms per mile. This line was 9½ miles in length. When measuring with both lines,—out one line and back the other, a total distance of 19 miles, the zero phase sequence reactance per phase was found to be 1.59 ohms per mile. With two lines in parallel, a total distance of 9½ miles, it was found to be 1.30 ohms per mile. It was found that if all three conductors of one line be used as an artificial ground wire for the other line, they will together carry about 50 per cent of the total return current. From this it appears that no matter how elaborate an arrangement of ground wires is installed, it is probable that the earth will carry at least one-half of the ground current at the time of a fault. The 2/0 HTBB overhead ground wire installed on the Lighthipe-La Fresa line carried from 20 to 30 per cent of the total return current. This ground wire current was not uniform along the ground wire, but decreased from the source end towards the grounded point,—the value at the grounded point being about 70 per cent of that at the source end.

66-Kv. System

The 66-kv. network has been rearranged considerably during the past few years, particularly from the standpoint of routine operation and protection. Previous to about four years ago, the 220-kv. to 66-kv. transmission receiving stations were interconnected quite closely on the 66-kv. side with the 66-kv. distribution stations looped into these connecting lines. The general practise was to have two or more incoming 66-kv. lines to each substation. This resulted in a closely coupled 66-kv. network between the various receiving stations and the condition that a fault on any of the 66-kv. lines affected all of the 220-kv. receiving stations. The magnitude of the short-circuit currents was increasing rapidly, and it was evident that some change would be required if we could hope to hold these fault currents down to a reasonable value. Reliance was placed upon directional power protective relays to isolate faults, but due to the necessity of progressive timing for selective operation, the possibility of quickly isolating extremely heavy short circuits adjacent to the 220-kv. receiving stations became more difficult. These receiving sta-

tions being the source of supply for the 66-kv. network, of necessity had to have the longest time setting when any form of protective relays embodying progressive time setting was used. Accordingly, in 1926 it was decided to begin changing the 66-kv. system from a loop system wherein the 66-kv. distribution stations were supplied from adjacent receiving stations, to a radial system wherein each of the 66-kv. distribution stations was to be supplied by two or more 66-kv. lines radiating from one of the receiving stations. Furthermore, every effort was to be made to limit the phase-to-phase or phase-to-ground 66-kv. short-circuit current to approximately 1,000,000 kv-a. with an occasional exceptional upper limit of 1,500,000 kv-a.

With the radial scheme of operation where two or more lines radiated from the major receiving station to a 66-kv. distribution station, it was no longer necessary to rely upon power directional relays progressively timed, so advantage was taken of the characteristics of current balanced relays wherein the currents in corresponding phases of two or more lines were balanced against each other. This permitted a more prompt clearing of 66-kv. faults with a consequent improvement in system operation. This changing of the transmission system has been going on steadily since 1926, and at present is fairly complete in the central portion of the 66-kv. 50-cycle system. Reference to Fig. 2 will show the system at present, and it will be noted that out of Eagle Rock, Laguna Bell, Lighthipe, Long Beach No. 2, and La Fresa substations pairs of radiating lines are quite general. In a number of cases the 66-kv. substations can be supplied from two of the major receiving stations, and at these sectionalizing points one set of oil circuit breakers is opened or the bus is split so that under normal operating conditions the station is supplied from only one receiving station. This change in transmission line connections and in the method of operating the 66-kv. network has resulted in a marked improvement in service and a decided limitation of a 66-kv. disturbance to a comparatively small area. The decrease in the short-circuit current and particularly the increased speed of clearing short circuits due to the use of current balance relays has resulted in a marked decrease in the tendency towards system instability at the time of 66-kv. faults. As an adjunct to the current balanced relays, current balanced residual or ground relays are installed when necessary, and provision is made to maintain protection by means of over-current or power directional phase or residual relays for single-line protection.

16-Kv. and 11-Kv. Systems

Heretofore the usual method of providing for supply to 16-kv. or 11-kv. substations was by means of a separate feeder or a tap off of a feeder radiating from a 66-kv. substation. During the past two years steps have been taken to provide two or more sources of supply to these lower voltage substations, using either a scheme of loop operation between two 66-kv. substations, or the preferred and emergency supply method of operation. Recent analysis of the status of these lower voltage substations supplied from the major 66-kv. stations shows that at present there are thirty-five distribution substations now being operated on the loop system, of which twenty-four stations are operated on the 16-kv. system and eleven on the 11-kv. system. The maximum transformer installation is 12,000-kv-a. and the minimum is 750 kv-a., and the total transformer capacity aggregates 139,150 kv-a. There are ten distribution substations now supplied by the preferred

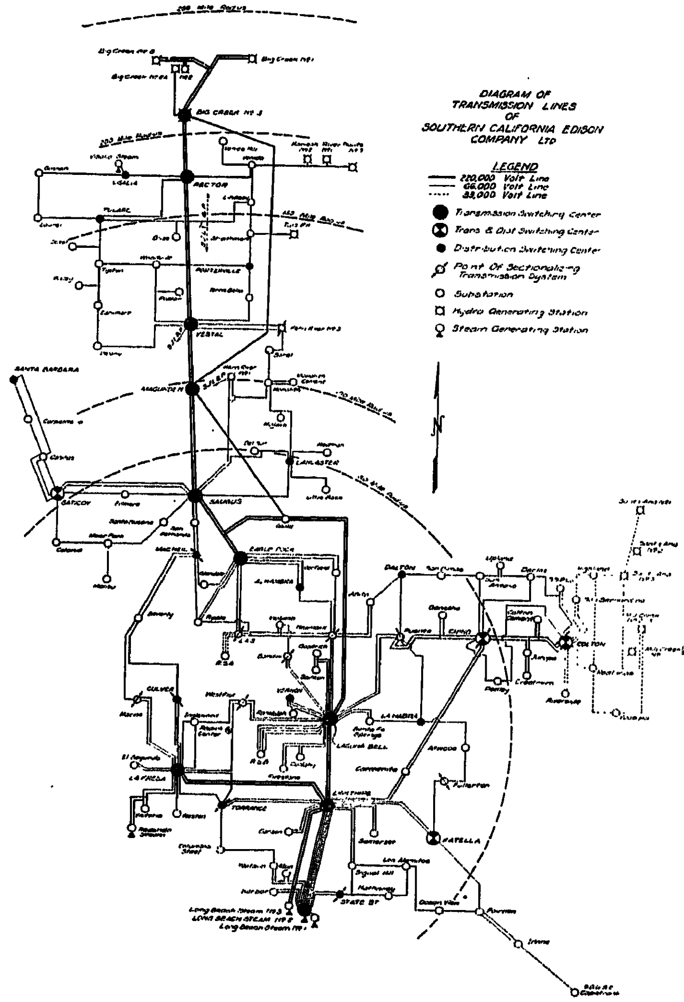

Fig. 2—Diagram of Transmission Lines of the Southern California Edison Co., Ltd.

Showing general scheme of 66-kv. parallel line supply to substations adjacent to major receiving stations

and emergency operation scheme. The maximum installation has a capacity of 3,000 kv-a. and the minimum 750 kv-a., and the total capacity of these substations amounts to 18,750 kv-a.

An analysis of the cases of trouble experienced on lines supplying the stations operating on the low-voltage loop connections shows that during the first six months of 1930, 38 cases of trouble were experienced, and 31 out of the 38 cases were cleared correctly. In analyzing the seven cases which did not operate correctly, it was found that two were caused by mechancial trouble with

the oil circuit breakers, two by incorrect relay wiring, one by insufficient ground current, one by the direct current trip circuit being de-energized, and one unknown. The above record shows that there is some room for improvement, but the results were so much more satisfactory than what would have been experienced had the substations been supplied from a single radial line as had been the practise in the past, that it is felt that loop operation of low-voltage distribution substations is successful and should prove a very prominent factor in minimizing service interruptions.

An analysis of the experience with the preferred and emergency scheme of operation shows that during the first six months of 1930 there have been five cases where the supply had to be changed over, and the only case of trouble experienced so far has been due to a minor mechanical adjustment causing one of the stations to fail to function properly. The mechanism of the preferred and emergency service scheme is so adjusted that the station supply is interrupted for such a short time that the interruption is not noticeable, for tests show that the time required to change from a deenergized line or the line in trouble, to the energized or emergency line, is approximately 18 cycles on a 50-cycle system. This small interval of interruption is barely enough to cause a perceptible voltage dip.

Operating Experience

Careful records of the performance of protective relays and automatic oil circuit breakers have been kept for the past several years. Table IV is a tabulation of

TABLE IV
OPERATION OF PROTECTIVE EQUIPMENT
220 Kv. to 11 Kv. Inclusive

	Year				
	1925	1926	1927	1928	1929
Cases of trouble	1493	2185	1799	1415	1303
Automatic switch operations	2368	3231	2831	2085	1923
Unnecessary switch operations	278	316	287	151	70
Failure of switches to operate	50	47	48	25	33

the experience through 1929. It will be noted that the trend is towards fewer cases of trouble and consequently, in general, fewer automatic switch operations. There has been a decided decrease in the unnecessary switch operations which shows the result of wider application of protective relays together with more knowledge of their characteristics and limitations. Intensive studies of the magnitude and distribution of phase-to-phase and phase-to-ground short circuit currents have been of immense value in determining proper relay settings for various types and locations of faults. The decrease in "failure of switches to operate" has not been so marked. These failures are in general the result of some form of trouble on the tripping side of the protective relays. A tripping coil may become defective, an auxiliary switch in the tripping circuit may not be making proper contact, mechanical faults may develop in the oil circuit breaker operating mechanism, or the control wiring may be defective. A program of inspection, testing and careful maintenance of the oil circuit breakers, protective relays, and tripping circuits is the only means of lessening these "failures to operate."

Protective Equipment—General

In addition to protective relays and automatic oil circuit breakers there is certain allied protective equipment which must be considered as part of the necessary apparatus to provide against abnormal conditions. Current limiting reactors, lightning arresters, ground detectors, and grounding banks fall in this class. Table V shows the amount of protective equipment in service from year to year since 1925. It will be noted that the amount of equipment in service has, in general, increased steadily each year. This is to be expected as

TABLE V
PROTECTIVE EQUIPMENT IN SERVICE

	Year				
	1925	1926	1927	1928	1929
Protective relays	3562	6631	7600	7844	9180
Automatic oil circuit breakers	1961	2129	2464	2707	3043
Lightning arresters	592	685	1054	1243	1268
Current limiting reactors	63	68	84	112	155
Feeder ground detectors	80	88	94	87	77
Feeder grounding banks	..	..	..	..	9

it is consistent with the growth of the system. The exception is in the case of the number of feeder ground detectors and is the result of changing the transformer connections from isolated delta to grounded Y for the feeder supply in a number of the distribution substations. With grounded Y supply there is not the necessity for ground detectors as in the case with the other form of connection.

Remote Alarms

In unattended distribution substations located in rural districts a marked improvement in decreasing the length of a feeder interruption has been accomplished by installing remote alarms to the nearest attended substation. Where available, the existing private telephone lines between the attended and unattended stations are used to transmit the signal. Auxiliary switches on the feeder oil circuit breakers in the unattended substation are connected so that the opening of the oil circuit breaker closes the contact from the two telephone wires to ground, thence over the telephone wires to a source of low-voltage direct current and a relay with a bell alarm located in the attended substation. After this signal is received the station attendant can connect with the district headquarters and a trouble man is sent out to determine the cause of the interruption.

In a number of cases the unattended substations do not have telephone connections. To obtain an alarm without the necessity of building telephone lines it was decided to take advantage of another application of

vacuum tubes and to install carrier current alarm equipment. Recently orders have been placed for seven transmitters, five single and one double receivers. In general the alarm scheme is the same as the one utilizing telephone wires. There will be installed at each unattended substation a carrier current transmitter which will operate from the auxiliary switches on the oil circuit breakers. A receiver to receive the signal and operate the alarm will be installed in the attended station.

CONCLUSIONS

(a) In the interest of assuring a more reliable performance of the protective relays on the 220-kv. transmission system under conditions of testing and overhauling the protective equipment as well as during normal operating conditions, duplicate sets of relays are installed. This permits the protection to be retained at all times.

(b) The use of carrier current pilot protection on one section of the Vincent 220-kv. transmission line has been satisfactory and has shown the value of this form of protection under conditions which would not permit the use of other forms of protective relays.

(c) The use of current balanced relays and radial lines between the 220-kv. major receiving stations and the 66-kv. distribution stations has been an improvement over the previous practise of looping through the 66-kv. stations between adjacent 220-kv. stations. The elimination of the necessity of depending upon power directional relays progressively timed has speeded up the time required to clear faults.

(d) The practise of looping 16-kv. and 11-kv. distribution stations between adjacent 66-kv. stations in place of the previous practise of using single radial lines has resulted in a marked improvement in service.

(e) The use of a remote alarm between unattended and attended stations to indicate when an oil circuit breaker trips out at the unattended stations has lessened the time of outage considerably in rural districts. Private telephone lines or carrier current equipment coupled to the transmission lines permits the installation of this remote alarm at a reasonable expenditure.

ACKNOWLEDGMENT

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The Communication System of
The Southern California Edison Company, Ltd.

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Member, A. I. E. E. Associate, A. I. E. E.

Synopsis.—*This paper gives a general description of the Southern California Edison Company's communication system which not only meets the requirements of load dispatching but also serves to bring about close cooperation between the outlying district forces and their directing heads at division headquarters and in the general office. Decentralized dispatching which makes possible the restoration of service after an interruption without the immediate need for communication is touched upon. The detail of the development and construction by the Company of the "Serjdetour" arrester is made public for the first time. This piece of equipment has made possible a protective system which not only prevents damage to valuable communication equipment in stations for the extreme case of actual contact between telephone lines and power lines but also preserves continuity of communication service after power system disturbances which create surges of considerable magnitude on inductively exposed telephone lines. A brief outline is presented of the standardized assemblies of telephone equipment into units which are adaptable to wide variations in requirements by the use of different combinations and quantities of standard units. The communication building where the telephone system centers is described, together with the methods of handling traffic through this point. A brief description of the testing equipmens for initial tests on new lines and maintenance of existing facilitiet is given together with test results on a typical line 279 miles long.*

INTRODUCTION

IN general the communication system of a power company is not given the consideration it deserves; in fact, its existence is usually through necessity alone. In the case of a power company operating a transmission system covering hundreds of miles and extending to hydroelectric plants located in sections remote from population centers, it is very unlikely that commercial communication facilities will be available, and therefore the power company builds telephone lines to the points where service is needed. The tendency has been to construct these lines as cheaply as possible.

In most cases the lines are built jointly with power transmission lines where they are exposed to inductive interference to a maximum degree. Although commercial communication lines are constructed with as great separation from power circuits as practicable they are coordinated to minimize any interference, while power company communication lines with their maximum exposure to inductive interference are often given little attention in this regard. Realizing that such a communication system could not provide high grade service and that but a relatively small additional expenditure for proper construction and coordination would greatly enhance the value of the system, the Southern California Edison Company, in 1919, started toward this end by transposing the old 50,000-volt Borel line and the associated telephone circuit, which made it possible to carry on a satisfactory telephone conversation over the entire length of a line which previously could be used with difficulty only by relaying through an intermediate operator. This improvement was made necessary by the volume of traffic which had to be handled over the line in connection with the construction of the Kern River No. 3 power-house. As an outgrowth of the success in this first effort to improve the quality of communication, many very good lines, primarily for dispatching purposes, resulted in the following years. With this improvement an insistent demand was created for more telephone connections for various other services such as district offices, stores, etc., so that they might be used for company business when not required for operating routine.

It may be possible to operate the power system without an extensive communication system, but the continually growing complications of the power network and the progressive steps of other branches of the power company organization require closer cooperation between the branches, and this is accomplished through the medium of efficient telephone communication.

From such beginning the communication system of the Southern California Edison Company has grown until now it renders complete telephone service to all departments within the company, serving an area of 55,000 square miles through three 100-unit private automatic exchanges, a modern three-position tollboard and three outlying exchange centers. It involves 6,000 circuit miles of toll line, 400 circuit miles of cable and 1,400 telephones representing a capital investment of over two and one-half million dollars in communication plant. Fig. 1 illustrates the extent of the communication lines in conjunction with the power network.

While it is necessary for many reasons that the Southern California Edison Company provide its own communication facilities, it also makes use of the commercial facilities to supplement its own wherever they are available. Commercial telephones are located in many substations and in all district offices and stores so that in effect an independent duplicate telephone system is available for emergency use by long distance calls to many strategic points on the system.

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Decentralized Dispatching

The first and most important function of the Southern California Edison Company's communication system is to provide direct connections between the supervisory dispatching center at Alhambra and the sub-dispatchers located at important switching centers; and of nearly equal importance is the necessity of a like service from the switching centers to the stations whose operation they direct.[1] Under the decentralized dispatching system now in use by this company, switching centers are located at the major distributing points which are required to reestablish service. However, it is also desirable that communication be available to all stations after an interruption so that the system may be promptly restored to normal operating condition.

Protection

The status of wire telephone facilities as to serviceability immediately after power system trouble depends on the design and proper operation of the telephone protective equipment. Since commercial communication facilities are generally separated from power systems by as much distance as is practicable, they have not

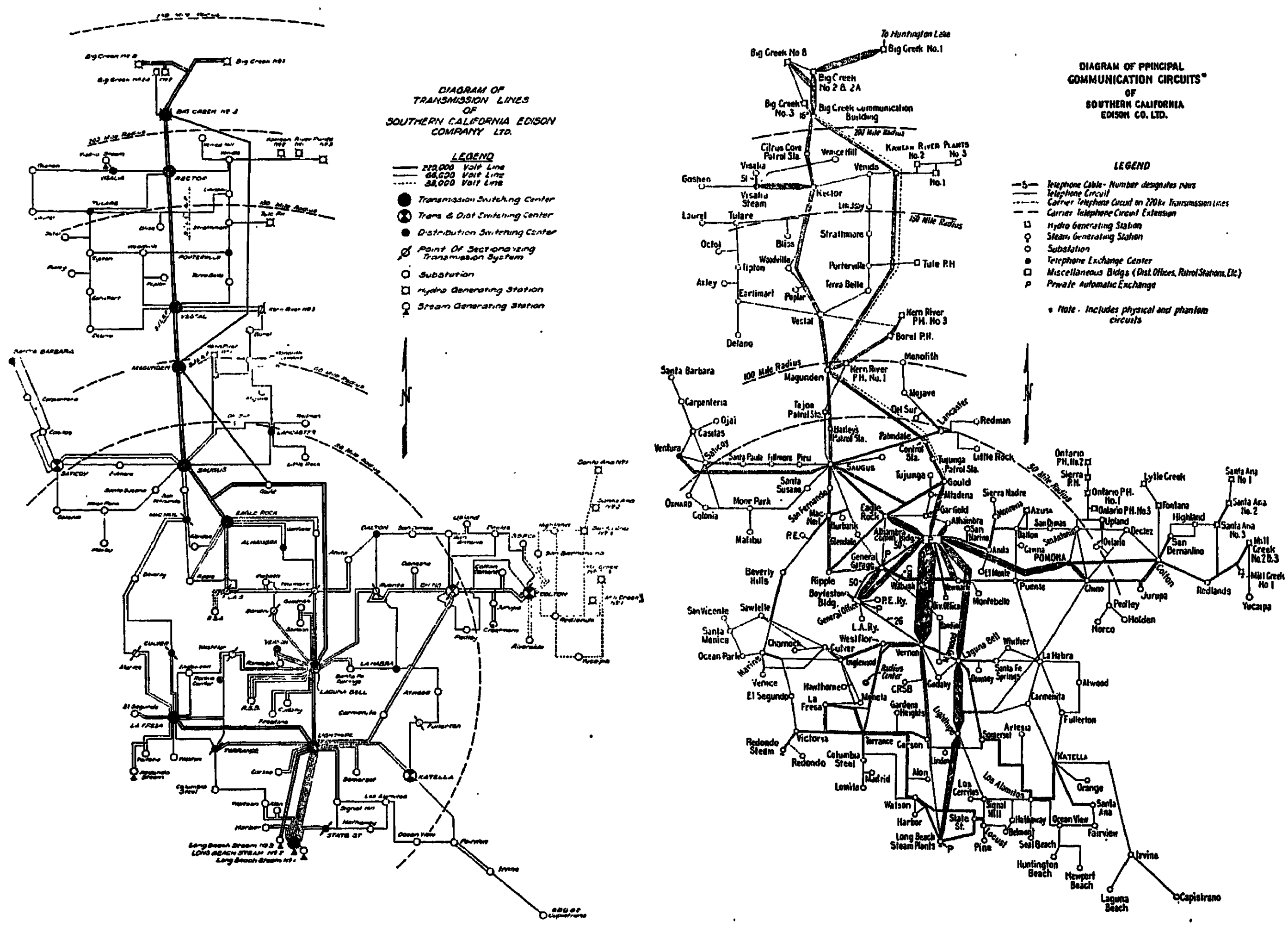

FIG. 1—MAPS SHOWING THE MAJOR TRANSMISION NETWORK AND THE IMPORTANT COMMUNICATION CIRCUITS

authorized to maintain service on all lines to stations within their jurisdiction. Eighty per cent of all the outlying stations are provided with one or more power lines radiating directly from the switching center, so that in the event of an interruption, service can be restored by the switching center without the need of communication. The remaining twenty per cent of the stations must be supplied with power from the switching center through an intermediate station and direct communication with outlying stations is often felt the need of high current capacity protective equipment, and hence this has not been obtainable from the manufacturers of telephone supplies. The chief requirements of protective apparatus for power system telephone lines are: first, that this equipment shall not be blown to pieces by the discharge resulting from direct contact between a telephone line and power line, and second, that it shall be capable of carrying the currents occasioned by induced surges arising from power system troubles without becoming internally short-circuited. As these requirements are not met by any commercially available protective gaps, it was

1. Decentralized Dispatching, by H. W. Tice, *Electrical West*, Vol. 63, No. 6, December 29, 1929.

necessary to develop a device to fill the need. After a great deal of experimentation there resulted a device which has been named the "serjdetour."

The serjdetour is capable of sustaining the discharge occasioned by contact between a telephone line and power line with no damage other than the welding together of the electrodes. When this occurs, it is only necessary to loosen four screws, remove the pitted electrodes, and substitute new ones. The device is then ready for service again. The pitted electrodes can readily be resurfaced in the shop.

While direct contacts between telephone and power lines occur occasionally the great majority of disturbances consist simply of induced voltages to ground or between wires due to exposure to power circuits under fault conditions. The discharge currents resulting from such induced voltages are much more moderate in value than those resulting from direct crosses, and the serjdetour is capable of handling these without becoming internally short-circuited.

This is an extremely valuable attribute, as it means continuity of communication service despite power system troubles. It has been determined by experiments that the current in our telephone lines during a power system fault will seldom exceed 25 amperes; so in many installations 25-ampere fuses are placed in the line. Then for the great majority of disturbances the fuses will not be affected. The serjdetour will carry the discharge for the duration of the power system trouble without becoming short-circuited. In the few cases where the current exceeds 25 amperes the fuses will blow before there is any danger of the serjdetour gap becoming short-circuited except in the case of a

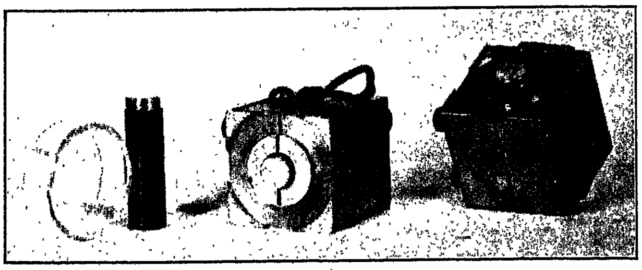

Fig. 2—The Component Parts of a Serjdetour Gap

Showing the Pyrex spacing ring, the silver tipped copper electrode, and the electrode mounted in its heat, absorbing block

direct cross, where it would not be reasonable to expect the gap to remain open. There is ample margin of safety here, as a serjdetour set to break down at 1,700 volts to ground will carry 50 amperes for several minutes without becoming short-circuited. If set to break down at 600 volts it will carry 20 amperes for a like time.

The construction of the Serjdetour is extremely simple. In its most commonly used form each unit consists of a group of three gaps, designed to be connected from each wire to ground and between wires, respectively. Each gap consists of a pair of cylindrical copper electrodes clamped in three-inch steel cubes. (See Fig. 2). The faces of these cubes are machined, and are held parallel by a Pyrex ring separator. This brings the faces of the electrodes into perfect parallelism,

Fig. 3—Cast Silver Electrode Showing Radial Cleavage Lines Caused by Heat and Beads Formed by the Concentration of the Arc on the Edges of these Lines

and the spacing between them is readily adjustable. The electrodes are tipped with pure rolled silver one-quarter inch thick, so that it is the silver which actually forms the arcing surfaces. The silver faces are machined with the greatest care to be perfectly flat, except for a slight beveling at the edges. They are given a mirror-like polish by the use of rouge. The success of the arrester action depends on the perfect parallelism of the faces and the smoothness of their surfaces. When these conditions are fulfilled the arc spreads uniformly over the entire surface of each electrode face, and so has no tendency to concentrate at one place and build up a projection. It is also essential that the silver faces be backed by the large copper electrodes and the massive metal blocks, as this insures that the heat is conducted away from the surface and absorbed in the blocks, thus avoiding undue melting of the silver.

The selection of polished rolled silver of great purity for the faces of the electrodes was the result of exhaustive experimentation and some study of metallurgy. Copper, zinc, tungsten, platinum, gold-silver alloy, hardy metal, and many other materials were tried. It was found that pits and beads were formed on the surfaces of electrode tips of these materials when subjected to an arc of 25 amperes. As the gap necessary for the required protective action is only 0.016 in., it was easily short-circuited by these beads. Of all the materials studied, the Hardy metal appeared to be much the best until tests were made on cast silver bearing a government stamp ".99997 Fine." This proved to be much superior in performance, although it did show a tendency to short-circuit under very heavy

currents. Microscopic investigation showed that the crystalline structure of the cast silver was such that under extreme heat radial cleavage lines were formed in the electrode faces. Minute cracks opened and presented sharp edges along which the arc concentrated, resulting in the melting of the silver and the

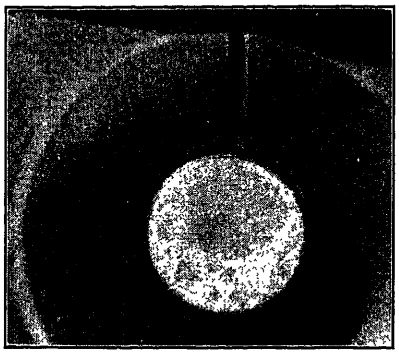

Fig. 4—Rolled Silver Electrode Subjected to the Same Test Given to the Electrode in Fig. 3

formation of beads. (Fig. 3). The substitution of rolled silver for cast eliminated this difficulty and gave a much improved performance. (Fig. 4). Further refinements were the polishing of the surfaces and the beveling of the edges, in order to avoid the slightest tendency of the arc to concentrate at any point.

The purity of the silver is a prime factor in the success of the serjdetour. Under the action of an arc, impurities seem to "boil up," causing projections which short-circuit the gap.

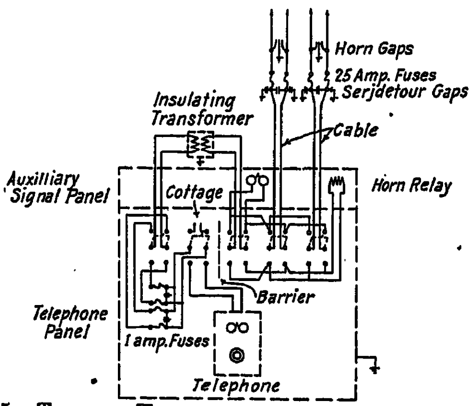

Fig. 5—Typical Telephone Circuit for a Substation at an Intermediate Point on an Important Dispatching Line

The serjdetour is, of course, not in itself a complete protective measure, but is the foundation unit upon which the protection system is built. The duty which this unit must perform is illustrated by consideration of Fig. 5, showing a typical telephone circuit for a substation at an intermediate point on an important dispatching line. For convenience in sectionalizing for test from a central wire chief's office, the line is looped through the switching panel in the station instead of merely being tapped. Continuity of service is a prime requisite; therefore no small fuses or protective gaps are inserted between the terminal pole and the switching panel. The serjdetour and its associated 25-ampere, 25,000-volt arc-quenching fuses are mounted on the

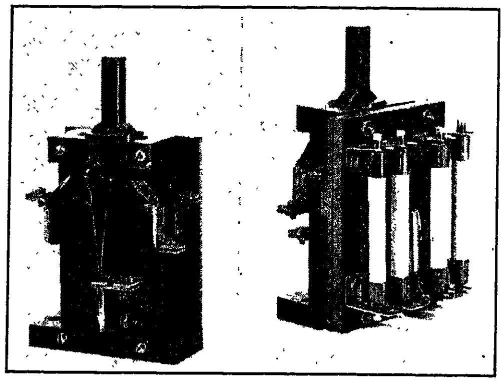

Fig. 6—Southern California Edison Company's Key Type Switch

Arranged for selecting either of two sets of fuses

terminal pole. The telephone instrument is insulated for potential from line to ground of 25,000 volts by the insulating transformer installed between the line

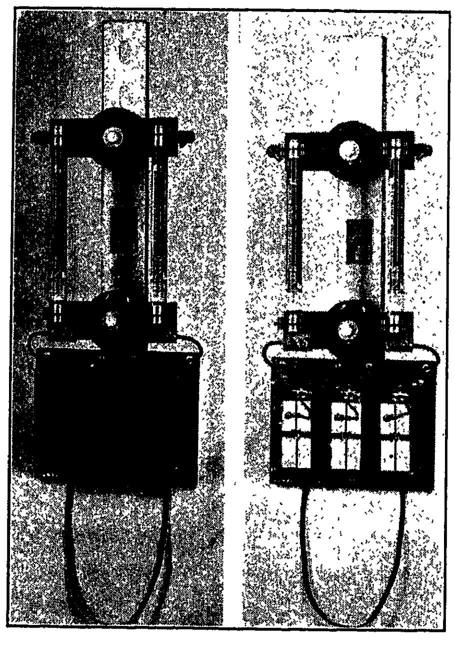

Fig. 7—Southern California Edison Company's Serjdetour Protective Unit

For use on exposed telephone lines

switching panel and the telephone panel. It is also protected from destructive between-wire voltage by duplicate sets of one ampere fuses and gaps, either set being selected by the fuse changing switch on the telephone panel.

Since the switches on the line switching panel are at

line potential, protection of the operator requires that live parts be covered and that operation of the switches be through a handle of ample insulating value. The switches Fig. 6, are double-pole, double-throw key type, and are operated by a long bakelite handle extending through the metal cover enclosing the entire grounded metal panel upon which they are mounted. The silver contacts have a wiping action to insure low resistance connections necessary to maintain balance, which is of great importance, in lines exposed to inductive interference. The lead-in cable from the terminal pole feeds through the back of the panel so that no part above ground potential is exposed.

The equipment on the line switching panel and the rubber insulated lead covered lead-in cable will withstand a potential of 1,700 volts to ground while the bells, relays and insulating transformers have been tested and found capable of withstanding 600 volts between wires. Thus it is required that the

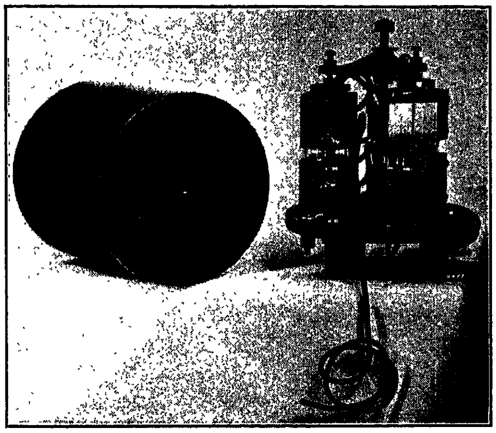

Fig. 8—Southern California Edison Company's Serjdetour Protector for Use with 14-Ampere Fuses on Unexposed Telephone Lines

serjdetour positively limit the voltage to ground to 1,700 volts and the between-wire voltage to 600 volts. To meet these requirements the serjdetour combination shown in Fig. 7 has been assembled. This consists of two gaps set for 1,700 volts and one gap set for 600 volts. The unit is combined with the 25-ampere, 25,000-volt arc-quenching fuses to form a protector unit for installations such as that just described.

In case of contact between the telephone line and the power line the 25-ampere, 25,000-volt fuses on the line side of the serjdetour will open and an arc will start at the horn gap arrester located on an adjacent pole, thus eliminating any tendency for flashovers on the terminal pole. An independent ground for the horn gaps is used in places where it is impracticable to connect to the substation ground network; because, should a ground connection be common to the horn gaps and the serjdetour and not connected to the station ground, current might flow across the horn gaps, the common ground connection, across the serjdetour gaps and thence through inside telephone equipment to the station ground after the fuses had opened. It is to be expected that the serjdetour gaps may be short-circuited in cases of direct contact between telephone and power lines; but the arrester still protects valuable inside equipment and the gaps may be cleared when the fuses are replaced.

For protection of equipment connected to telephone lines not paralleling power lines an arrester requiring less pole-top hardware is shown in Fig. 8, and is used in conjunction with 14-ampere telephone fuses. All three gaps in this arrester are set for 600 volts breakdown. The cables from the terminal poles to equipment panels in these cases may be paper insulated, as tests have shown that the 600-volt gap is adequate protection for the paper-insulated cable.

It may be of interest to cite an actual case wherein a boy threw a wire in such a way as to make contact between a 66,000-volt power line and a telephone line at a point 50 ft. from a terminal pole. No injury whatever was done to the cable or to the equipment inside the substation. Although the discharge current to ground through the serjdetour before the fuses opened was between 3,500 and 4,000 amperes, the device was uninjured except for the short-circuiting of the electrodes. The replacement of these electrodes and the two fuses restored the station to normal so far as the equipment was concerned, although the No. 8 copper telephone line wire fused a short distance from the arrester terminal.

During this same case of trouble, the fuses on the other end of the 15-mile telephone line were blown, but the serjdetour gaps were not short-circuited. Thus was illustrated the ability of the arrester to carry a current heavy enough to blow the fuses without short-circuiting the gaps.

The case described above is only one of a number of such major contacts handled by the serjdetour, in which no damage was done to valuable inside equipment; in fact, there has not been a single instance where equipment has been damaged since the serjdetour was adopted and connected to proper grounds.

It has been shown that the connections and the current carrying parts of the serjdetour must be of sufficient size to handle currents of large value. This idea of course, must be carried out in the entire ground system. Terminal poles frequently have as many as five or six terminating lines with the associated protective devices mounted thereon. The ground wire to these protectors consists of a No. 00 stranded copper cable. Precautions are taken to obtain the very best ground connection. Wherever possible, a tie is made with the station ground network. Connections are made by mechanical means rather than solder lugs. The horn gaps are given the same large capacity grounding treatment.

Carrier Current

On the 220,000-volt backbone of the system every

possible step must be taken to preserve continuity of communication. Owing to the mountainous nature of the country which the lines traverse, there is always the possibility of the telephone lines being damaged by sleet storms, brush fires, etc. Therefore it was considered advisable to install a carrier current telephone system. This extends from the Big Creek No. 3 hydro plant by way of the 220,000-volt Big Creek and Vincent transmission lines to Gould switching station near Los Angeles, with a wire extension to the supervisory dispatcher's office. An intermediate carrier current telephone station is provided at Magunden switching center.

The carrier current telephone system is of the single frequency duplex type coupled interphase to the 220,000-volt system by means of oil insulated tank type capacitors. Coupling is made to one of the buses and also direct to the Vincent transmission line at each station. This provides for clearing any bus or line for maintenance without interrupting communication since two complete carrier channels are available.[2] The coupling to the Vincent transmission line also provides a carrier frequency channel for the carrier current pilot protective system now in use on the 96-mile section of line between Gould and Magunden, an intermediate switching station. The carrier protective system is also contemplated for use on the section between Magunden and Big Creek No. 3. While the quality of voice transmission on the carrier telephone has been rather poor due to the very unequal attenuation of carrier frequencies included in the side bands, it has proved its worth on several occasions when after storm damage to the wire lines it was the only means of communication between the dispatcher and Big Creek. Careful investigation conducted with the cooperation of the manufacturer revealed that the very irregular attenuation of carrier frequencies differing by increments as small as 50 cycles, was due to reflection of the carrier from lines connected to the 220,000-volt system south of Gould and north of Big Creek No. 3. In order to correct this condition carrier frequency traps have been ordered and will be installed at Gould and Big Creek No. 3 to isolate the carrier communication channels from other parts of the system. It is expected that the installation of these traps will not only improve the quality of voice transmission but will also increase the ratio of signal to noise and reduce the effect of line switching conditions on the signal level.

Station Equipment

Due to the multiplicity of overhead power lines concentrating at substations, telephone circuits are completed from terminal poles to inside equipment panels through underground lead-covered cables. It has not been possible to obtain quadded cables with sufficient insulation for this use. Reduction of cross-talk to a satisfactory minimum, in the No. 14 rubber insulated lead-covered cable which is used, required that it be balanced and spliced at frequent intervals. Careful testing and splicing at the time of installation has produced highly satisfactory phantom groups in runs as long as 1,500 ft.

2. Carrier Current Pilot Protection, by E. R. Stauffacher and F. B. Doolittle, *Electrical World*, March 22, 1930.

Four general types of station equipment fulfil the requirements on the Southern California Edison system. The choice between types is determined by the amount of telephone traffic to be handled at each location.

The first and simplest type of equipment consists of a telephone enclosed in a weatherproof wooden box arranged for attachment to a pole. A switch is provided which automatically disconnects the telephone from the line when the door to the box is closed. One-ampere fuses and a between wire gap protect the instrument. A container holding spare fuses is provided. An insulating platform is attached to the pole

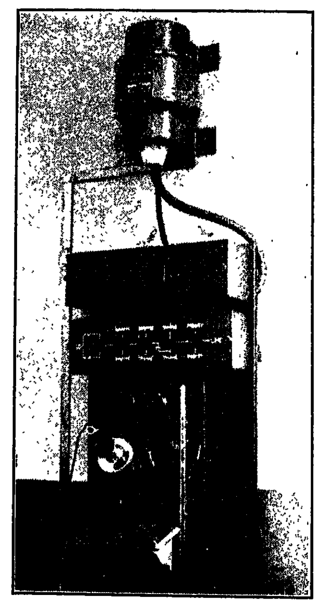

Fig. 9—Typical Installation of a Telephone Panel and One Auxiliary Signal Panel

to protect the user from voltage to ground. Pole box installations are made at outdoor unattended substations and at occasional pole-top switches on the lines from which points it is necessary for an operator to communicate with the switching center.

The second type of installation (Fig. 9) consists of a steel panel on which is mounted a telephone and five enclosed dead front switches. One switch is a fuse changing switch, the others being wired for an additional line, extension telephone or signal horn as a particular installation may require. A transformer insulates the telephone and local circuits from the incoming lines. One or more auxiliary signal panels equipped with bells and relays for horn signals may be added as required. Unattended substations, substations having but one operator who lives on the property, transmission patrol stations and other points using the te'ephone infre-

quently and having buildings available, are provided with such equipment.

Installations of this class may be extended to provide for terminating or looping more than two lines by the addition of one or more four-line panels depending upon the number of lines to be accommodated. The talking buses on the various four-line panels are paralleled and extended through the insulating transformer to the telephone panel previously described. Where four-line panels are installed no auxiliary signal and relay panels are used, as provisions for bells and relays are made in the four-line panels. An example of this is shown in Fig. 10.

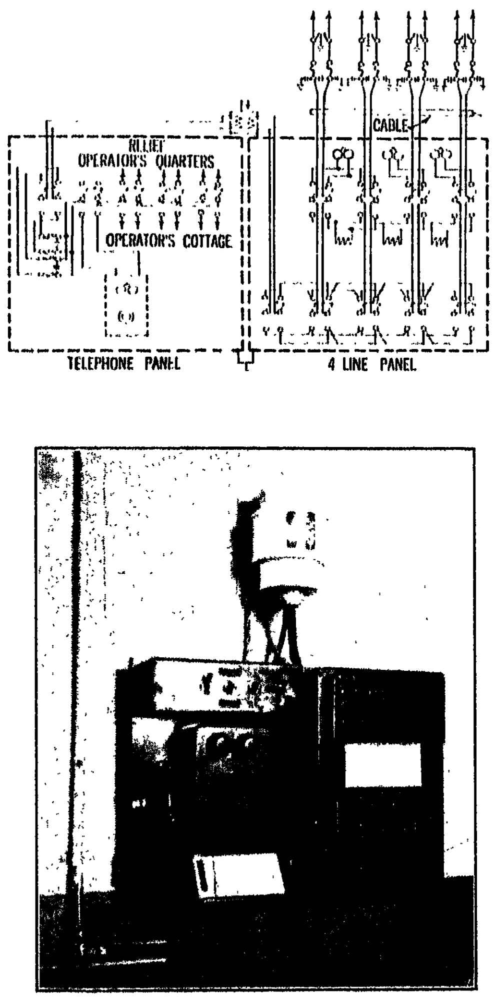

FIG. 10—TYPICAL INSTALLATION OF A FOUR-LINE PANEL AND CIRCUIT DIAGRAM

Showing one line looped through and two lines terminating

The third general type of installation is similar to the second, but because of more constant use of the telephone facilities, the lines are run from the four-line panels to dead front switches mounted on a desk. The desk, designated as type *C*, makes use of a turret equipped with eight line switches, a fuse-changing switch and a switch which connects the operator's telephone to either of two buses. A type *B* desk, similar to type *C*, but accommodating fifteen lines and providing four buses with the necessary switches mounted on a sloping metal panel built into the desk, is also standard equipment. The insulating transformer connected between the telephone and any of the buses is mounted in the desk of either type. These desks fulfil the requirements of the larger substations and switching centers using the telephone frequently but not required to do much telephone line switching.

The fourth and most elaborate standardized installation makes use of a desk type switchboard having a slanting key shelf accommodating twenty-seven lines and providing four buses for switching and two for talking. Each line position is equipped with three standard telephone keys, a white lamp which flashes the code rings and a red lamp which remains lighted for ten seconds after the termination of a ring to assist the operator in locating the line when he has heard his code call but did not see the white light. Bells mounted in the back of the desk give audible signals on the magneto lines, and the usual night alarm buzzers are used on the common battery lines. Each talking bus is equipped with an operator's telephone connection which includes an acoustic shock suppressor in the receiver circuit. The acoustic shock suppressor, developed by the company, consists of a vacuum tube amplifier circuit using low plate voltage so that the output of the amplifier is limited by saturation of plate current below such value as would produce acoustic shock on reaching the receiver.

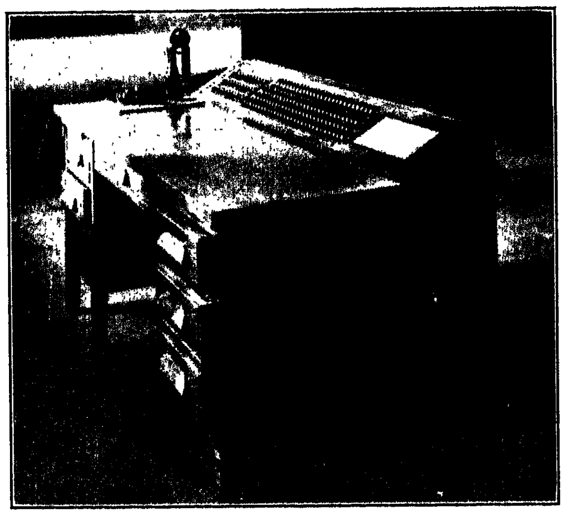

FIG. 11—TYPE A TELEPHONE DESK SHOWING KEYS AND LAMP SIGNAL ARRANGEMENT

The annunciator panel to the left of the key shelf is equipped with 30 positions, with space to the right for additional positions when required

This desk, known as type *A*, Fig. 11, provides an annunciator panel in addition to the telephone panel. On this panel are mounted lamps which give indications of power switching operations, transformer temperatures, etc. Both panels are built in and are completely wired to terminals in the back of the desk, Fig. 12.

From the terminals on the desk all the circuits are carried in cable to a cross-connecting box located in the rear of the equipment panels from which the various circuits may be jumpered to magneto line panels, common battery line panels, annunciator panels, relay panels, etc.

Unit type standard designs of equipment panels are available as auxiliary for this class of installation. They are mounted as required on steel racks which may be either set into a partition between two rooms or erected as self-supporting units, the back and sides of which are protected by a steel grill-work. A number of standard panels are listed and their purposes indicated as follows:

1. Power panels, on which are mounted series lamps for ringing power, alarm equipped fuses on the battery supply, auxiliary relays for alarms and relays for grouping the audible signals for several lines on one bell.

2. Auxiliary fuse panels, which are used when additional fused battery circuits are needed for annunciators, etc.

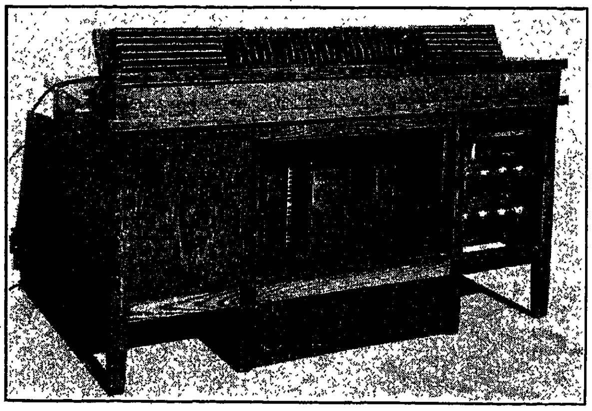

FIG. 12—TYPE A DESK SHOWING KEY SHELF RAISED AND BACK PANELS REMOVED

3. Magneto panels No. 1, on which are mounted alternating current line relays and their auxiliary relays for code lights and signals.

4. Magneto panels No. 2, on which are mounted pendulum and slow release relays for operating the red holding lights.

5. Common battery panels, are equipped with repeat coils, condensers and relays to accommodate five common battery lines to offices and cottages on the property.

6. Bell panels are equipped with six bells per unit.

7. Switch panels, which accommodate ten back-mounted dead front switches.

8. Telephone panels, on which are magneto telephones for testing and emergency use.

9. Fuse-change panels are equipped with duplicate sets of fuses, selected by switches, accommodating three lines. Three repeat coils are provided on these panels for connection of phantom groups.

10. Test jack panels are equipped with 15 pairs of jacks for testing and patching lines.

11. Test jack and patch panels, which are provided with three strips of twenty jacks for phantom patching and equipment testing.

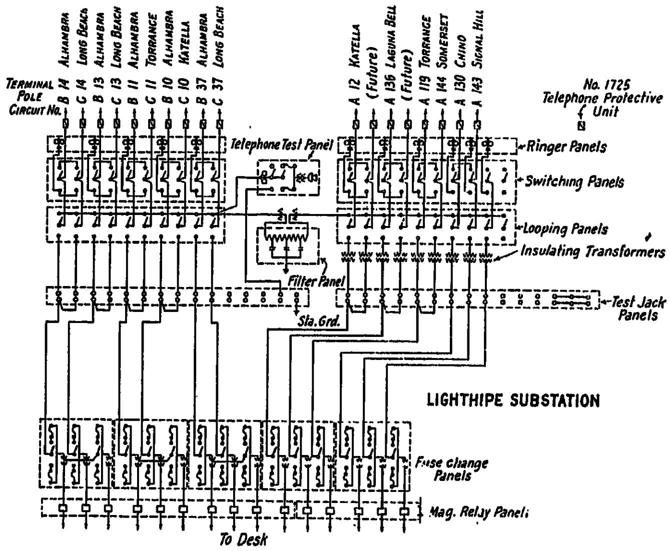

FIG. 13—SINGLE-LINE DIAGRAM OF A TYPICAL LARGE SWITCHING CENTER

12. Low pass filter panels, which are equipped with 40-cycle cut-off low pass filters for use when making bridge tests on lines when induced voltage to ground is present.

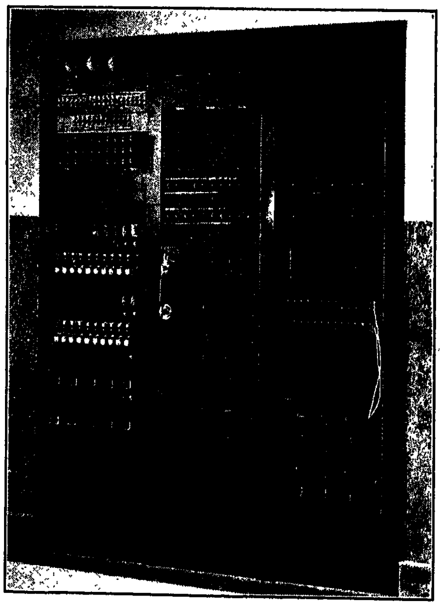

FIG. 14—FRONT VIEW SHOWING THE UNIT TYPE EQUIPMENT PANELS WITH SOME OF THE RELAY COVERS REMOVED

13. Miscellaneous blank panels are used to fill up excess space in the racks.

A single-line wiring diagram (Fig. 13) and illustrations (Figs. 14 and 15) of a typical installation of this equipment are shown. It may be observed that

insulating transformers are provided for all the exposed lines, which permits their safe interconnection with unexposed and common battery lines.

The flexibility permitted by assembly of these standard units to fit various requirements makes this equipment adaptable to the needs of the largest substations and switching centers. With the substitution of a cordboard for the desk, to permit more cross con-

FIG. 15—REAR VIEW OF THE EQUIPMENT PANELS SHOWING THE METHOD OF JUMPERING FOR INTERCONNECTION OF THE VARIOUS UNITS

necting, the same equipment is used in exchange centers. In cordboards the code lamps and holding lamps are associated with their line jacks. An acoustic shock suppressor is provided for the operator's protection. All equipment other than the cord circuits and signals is located on the equipment panels.

EXCHANGE CENTERS

The communication facilities required for other than dispatching the immediate operation of the power system are provided in a manner similar to that of commercial toll service. The term "toll" as used hereafter applies to service between different localities, that may be handled on a delay basis. For operating and commercial purposes, the Southern California Edison system is divided into six divisions and thirty-two districts. The communication facilities for the Eastern Division (Fig. 16) will be described as typical of a division's requirements. The division manager and the division superintendents of distribution, substation operation and transmission, and their clerical assistants, are located in adjoining offices at division headquarters.

In the outer office, where the operator may also serve as information girl for the division personnel, a telephone exchange board is located. Nine magneto party lines radiate from this switchboard, to the district commercial offices, superintendents' offices, stores, and substations. Ten common battery lines provide service to the local telephones and five toll trunks connect this exchange center with the main communication center at Alhambra.

The reason for the high per cent of trunking is that some departments, such as the general store, transportation and medical, have no division heads and require communication through the exchange centers to their individual district men.

At commercial offices and stores several desk telephones are provided rather than a single booth because the circuit time saved in getting the called party promptly, justifies the cost of the additional instruments.

COMMUNICATION BUILDING

The impracticability of maintaining many overhead telephone circuits to the general office building in downtown Los Angeles, and the risk of loosing all the circuits at once should anything happen to an underground cable which might contain them, as well as the higher transmission loss in such a cable, were the factors whose consideration lead to locating the communication center and supervisory dispatcher's office at Alhambra, a point accessible to the overhead lines, and some 12 miles from the general office. To properly house the facilities for this purpose a modern fireproof structure was built and is known as the Communication Building. The space on the ground floor of the building is occupied by facilities of the Communication Department, consisting of equipment panels, the wire chief's testboard, the power switchboard,

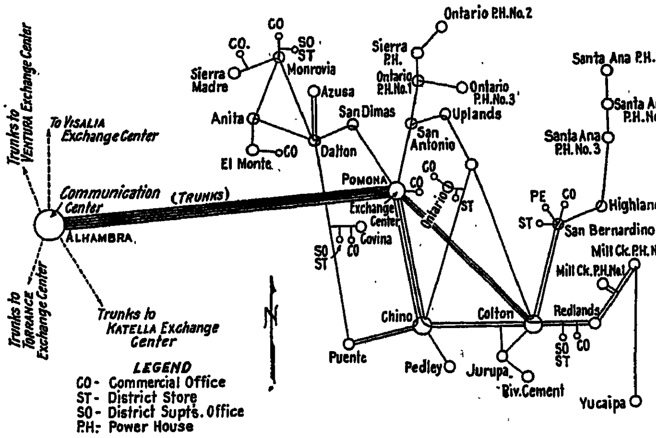

FIG. 16—LAYOUT OF CIRCUITS SERVING THE EASTERN DIVISION

motor-generator sets and storage batteries, the private automatic exchange serving the company's plant on adjacent property, as well as office space for the department's personnel, storage space for equipment and supplies, and the communication laboratory. On the second floor of the building are located the supervisory dispatcher's office and the main toll switchboard together with kitchenettes for the personnel of each and a

comfortably furnished rest room for the toll operators.

The telephone circuits terminating at the communication building are protected and carried in underground cables to the equipment panels just as in any large substation installation. From these panels they are distributed to the dispatchers' desks, the toll board and the wire chief's board. Many of the long lines are party lines and ringing on them is so frequent that it would be confusing to the dispatchers and toll operators if they received all the signals. To avoid this confusion, a selective device operated by the ringing current and consisting of relays and a rotary line switch discriminates between the code rings and brings in the line lamp on only the particular board desired. The result is that in so far as the dispatchers and operators are concerned, the lines do not appear as party lines, their lamps lighting only when they are wanted and remaining on until they are answered.

Three 25 line key-operated desk switchboards provide a means of establishing direct connections from the supervisory dispatchers to the switching centers. These desks are similar to those described for the largest substations but have an additional feature which is a toll line selector. By dialing the circuit number on this selector, all of the lines terminating at the communication building are available to the dispatchers. In effect each dispatcher has a 100-line switchboard within a very small space.

The three-position toll switchboard provides a connecting link from the intercommunicating systems serving the general office, general garage, and Alhambra properties, to the toll lines. A manual exchange handles the intercommunication in the present general office while this service is provided by private automatic exchanges located in the general garage and in the communication building, the latter serving the general store, shop, test and transmission departments. The new Edison building now under construction will be equipped with a four hundred line private automatic exchange.

Traffic through the toll switchboard is handled in a manner similar to that used by the communication companies. A call originating from one of the intercommunicating lines is recorded by one of the toll operators who completes the call direct from the recording trunk if possible or calls back as soon as the connection can be made. Each call is recorded on a toll ticket giving the time the call is placed, the time the connection is established, the duration of the conversation and the trunk and circuit numbers involved. Space on the back of the ticket is used to record the cause of any delay encountered in completing the call. These data are used for traffic studies and sometimes to call the attention of employees to negligent or careless use of the communication facilities which, if continued, would result in waste of valuable circuit time.

The wire chief's board is located adjacent to the equipment panels, Fig. 17, making it convenient for the wire chief to do any line switching or patching which may become necessary. The usual testing facilities consisting of a standard voltmeter and bridge, together with some special testing equipment, are provided on the two-section wire chief's board. Since the toll board is operated only during working days, ten cord circuits and a switching arrangement to bring in line lamps on the wire chief's board are provided so that the wire chief may maintain 24-hour toll service without the necessity of toll operators during periods of light traffic. All lines, including phantoms, are looped through in, out, and multiple jacks. Associated with each set of jacks are four lamps, being, respectively, the code lamp indicating the code signal rung, the selector lamp showing the operation of the selector when the dispatcher or toll operator is to answer, the busy lamp, and the monitor lamp which shows the position of the automatic monitor. The automatic monitor is a device which connects the wire chief's head phone consecutively to each line for an interval of one second or three seconds. It may be stopped, started, make one complete cycle of one hundred lines, repeat, or the interval changed by the operation of three keys. Use of this equipment permits the wire chief to write up trouble reports or do other clerical work and at the same time to subconsciously note anything unusual that may take place on the lines.

Fig. 17—The Wire Chief's Test Board and the Conveniently Located Equipment Panels

The wire chief is to the communication system what the load dispatcher is to the power system. His first duty is to maintain continuity of service on important dispatching lines which he does by switching and patching with less important lines whenever this is possible and there is trouble on a dispatching line. He is responsible for maintaining normal condition and continuity of communication channels over the entire system. This he does with the aid of two sub-wire chiefs, one being located at Big Creek and responsible for the communication facilities at the Big Creek power plants, the other being located at Vestal substation at

which point is located the communication center for the company's system in the San Joaquin Valley. The men responsible for these portions of the system make a daily report of the status of communication plant in their respective territories which combined with similar information obtained by the wire chief himself for his territory together with records of the previous day's troubles form a daily report to the superintendent of communication. In addition to these daily checks of all communication channels, the wire chief makes periodic routine tests of a quantitative nature to detect any deterioration affecting communication. Where minor routine maintenance will bring the facilities back to normal, it is performed under the wire chief's direction, otherwise it is reported to the superintendent of communication who receives authority from the communication committee at one of its weekly meetings to make an application for an expenditure to handle major reconstruction. The superintendent of communication is responsible to the manager of operation for the personnel, operation and maintenance of the communication system. The manager of operation is chairman of the communication committee which does the planning of future additions to the communication system. The requirements are based upon the wire chief's reports together with traffic studies compiled from data furnished by the chief toll operator, and extensions of the power system.

Line Testing and Results

When a new telephone line is constructed, it is tested in its entirety and in sections before it is accepted for operation. Any changes or corrections for improvement are made before it is put in service. A folder showing the route of the line, pole numbers, distance between poles, type of construction, size of wire and transposition scheme together with a report of the initial tests is made up at this time and filed where it is available to the wire chief thus providing records for reference in maintaining lines up to standard.

For the purpose of making the initial tests as well as for use in maintaining and improving existing facilities, a test truck is maintained by the communication department. All of the instruments necessary for complete line testing are permanently mounted in this truck and are wired to convenient terminals from which jumpers are run to the lines. The equipment for properly terminating the far end of the line under test is mounted and permanently wired in a box of such size as to be portable in an ordinary passenger automobile.

The following tabulations give the results of an overall test on a four-wire telephone line between Alhambra and Big Creek, a distance of 279 miles. The line follows the general route of a 220,000-volt transmission line. It is constructed of No. 8 copper wire in the light loading sections and No. 6 copper wire in the heavy loading sections. It loops through three major switching stations and four patrol stations.

Insulation resistance	365 megohms per mile
Resistance unbalance Circuit No. 1	1.3 ohms
Resistance unbalance Circuit No. 2	0.8 ohms
Resistance unbalance phantom	0.3 ohms
Cross talk side to side	220 cross talk units
Cross talk circuit No. 1 to phantom	500 cross talk units
Cross talk circuit No. 2 to phantom	800 cross talk units
Noise, metallic circuit No. 1	250 noise units
Noise, metallic circuit No. 2	150 noise units
Noise, metallic phantom	150 noise units

The transmission equivalents including equipment are:

Circuit No. 1	15.85 decibels
Circuit No. 2	15.88 decibels
Phantom	13.15 decibels

This is representative of lines of this class and length, however other more recently constructed lines have better characteristics.

Conclusion

By proper attention to coordination and maintenance of good balance the communication lines of a power company may be highly satisfactory in spite of their severe exposure to inductive interference because of their proximity to high-voltage lines. Their serviceability immediately following power system disturbances involving high induced voltages on the telephone lines depends upon the effectiveness of the protective system. The serjdetour arrester and its associated equipment provides a protective scheme which will maintain continuity of service despite power surges of magnitudes ordinarily encountered and will protect inside equipment from damage in the extreme case of contact between telephone lines and power lines. A comparatively few assemblies of equipment into standard units provide economical material which is adaptable to installations of widely varying requirements and magnitudes. Original testing and maintenance of lines to the original standards by subsequent routine tests keep the facilities in first-class condition. Several years' experience with a constantly improving communication system have demonstrated that good telephone communication promotes close cooperation between departments of the company to the end that better service may be rendered to consumers.

Discussion

E. L. White: While my own Company operates in the north near Puget Sound, and the Southern California Edison Company operates far south of here, I note that we have many similar problems. In particular, the question of adequate protection seems to be common. After much experimenting, the Southern California Company has arrived at the serjdetour, which appears to be more than adequate for the duty it has to perform. In our own case, we have modified the standard horn gap and equipped it with a small gap between wires, in addition to the two gaps already existing between the two wires and ground. Our normal gap setting is approximately 1/32 in. on all three gaps. Closer settings are inadvisable because of possible trouble from dust, lint, and other materials.

R. D. Evans: An interesting feature of the paper is that concerned with the measures for protecting power-line com-

munication systems from induction. It may be of interest in this connection to describe briefly some other protective systems which have been in successful use.

Supervisory control lines are subject to induction in much the same way as the power company telephone lines described. An important requirement of the protective apparatus is that of low maintenance on repeated discharge of relatively high-current capacity. In connection with our supervisory control lines, we have been using successfully a tube type of protector which is capable of discharging 50 amperes for two seconds repeatedly without injury to the electrodes and without change in characteristics for subsequent operation.

In some applications supervisory control circuits are subjected to relatively high sustained fundamental frequency induction of the magnitude of say 1,000 volts. A particular case was solved by the use of drainage in connection with tube type protectors. This supervisory control circuit being operated with direct current signaling made it necessary to introduce a resistance between the lines and ground in order to prevent by-passing too much operating current from the relay. The tube protectors, of course, are not operated except in the event of abnormal induction as under short-circuit conditions in the neighboring power supply circuit. This drainage system has been in successful operation for some time and has provided a simple and practical solution of the relatively severe induction condition on supervisory control circuits.

R. B. Ashbrook and F. B. Doolittle: Referring to Mr. White's discussion, it is our experience that the use of horn gaps alone for telephone protection is insufficient. In the case of direct contact between telephone circuits and high-voltage power lines the horn gap does not serve as a definite voltage limiting device but allows the voltage to rise as the arc lengthens due to traveling upward toward the points of the horns. Consequently it does not protect telephone cable and inside equipment from damage under this condition.

The use of horn gaps as a part of the protection scheme of the Southern California Edison Company is to provide a path for the discharge current after the 25-ampere, 25,000-volt fuses associated with the serjdetour have opened, thus eliminating any tendency for flash-over at the fuse mountings on the terminal pole. The horn gaps are mounted on an adjacent pole ahead of the fuses.

The Pennsylvania Railroad Electrification

BY J. V. B. DUER[1]
Fellow, A. I. E. E.

Synopsis—*This paper covers the electrification program of the Pennsylvania Railroad and consists of a brief explanation of the reasons for the decision to embark on this electrification program, a review of the operating experiences leading up to the present designs used on the railroad, of catenary and transmission circuits, substation layout and types of equipment, as well as a description of the progressive steps of electric locomotive design which preceded the development of the electric locomotives to be used in this program, and concludes with a brief resumé of the points that should be given attention in applying an electrification to a stretch of railroad.*

* * * * *

On October 31, 1928, General W. W. Atterbury, President of the Pennsylvania Railroad, announced that the Board of Directors had authorized a program of electrification, over a period of years, of the entire road train service, freight and passenger, between New York and Wilmington, Delaware, as well as the electrification of the grades between the Susquehanna, Schuylkill, and Delaware River Valleys, and the Eastern Terminal of the Railroad; a project covering a passenger and freight service of 325 mi. of line and 1300 mi. of track and extending from Hell Gate Bridge in New York, where connection is made with New England, west and south to Wilmington and west on the main line in the direction of Harrisburg.

The authorization of the Board of Directors to inaugurate this electrification work followed exhaustive studies of the whole industrial and transportation situations in the eastern part of the country, including the terminal developments already under way or projected for Philadelphia and Newark. While this analysis was worked out in detail, on the basis of the traffic estimated for the year 1935, the probability was not lost sight of that by 1950, the metropolitan area around New York would extend to New Brunswick on the west and well out on Long Island on the east and contain 30,000,000 people, and that there would be similar developments in other cities.

The system adopted is such that by the simple addition of increased power and increased rolling stock, a movement of any magnitude which it is possible to transport over the existing tracks and at a speed within the bounds necessary for safe operation may be handled as the demands of the traffic may from time to time require. The immediate factors which influenced the decision to proceed with the electrification were as follows:

1. The greater economy of electric traction as compared with steam operation in dense traffic territory.
2. The growth of the southern passenger business.
3. The increasing density of both freight and passenger business on our eastern lines and the probability that in the future more rapid movement would be required.
4. The desirability of utilizing the advantages of electric traction in connection with the construction of the new passenger terminals at Philadelphia and Newark.
5. The desirability of building a locomotive that would meet the requirements from the standpoint of weight of train, speed, and reliability which it is believed will have to be met in this territory in the next twenty years.
6. The probability that the project could be completed with a less total expenditure, all matters considered, than if started at a later date.

Of this program, the electrification of the New York Division, from Philadelphia to Trenton, has been completed and electrical suburban service inaugurated; electrification of the Schuylkill Division from Philadelphia to Norristown has been completed and electrical suburban service inaugurated; and at the present time electrification work is progressing from Sunnyside Yard and Jersey City to Manhattan Transfer and New Brunswick as an initial step in the operation of trains by single-phase locomotives from New York to Philadelphia, and for the operation of our suburban service between Jersey City and New Brunswick with single-phase multiple unit trains.

The announcement of this electrification program is the sequel to an interesting story of operating experience, of trial of electrical equipment, and of design and experimental work which started in 1905 when the Long Island Railroad was electrified, and which extends down to the present time when our electrification program is well under way and which covers experiments with d-c. electric locomotives and a complete trial of the single-phase system.

During the course of these experiments, an especially equipped section of the Long Island Railroad was used to develop the possibilities of this system, which, while not used for initial operation in the New York tunnels, was adopted shortly thereafter for the electrification of the suburban lines around Broad Street, Philadelphia. It has now been selected as our standard system for use in the electrification program upon which this railroad has embarked.

To be prepared for an extensive electrification, it was necessary to develop single-phase passenger and freight electric locomotive designs, as well as multiple

1. Elec. Engr., Pennsylvania Railroad Co., Philadelphia, Pa.

Presented at the Pacific Coast Convention of the A. I. E. E., Portland, Oregon, September 2-5, 1930.

30-153

unit car designs, and accordingly, in 1917 a constant speed, split-phase electric locomotive, (railroad classification FF-1,) was designed, built and tried out in service. The experience with this locomotive led to the development of a commutator motor type locomotive (railroad classification L-5) of somewhat less horsepower than the constant-speed locomotive above referred to and having the variable-speed characteristics which experience seemed to teach were more suitable for a railroad handling a dense passenger and freight traffic.

Locomotives of this design were built and placed in service on alternating current in the Philadelphia territory, and on direct current in the New York Terminal. They proved satisfactory and have given good service, and to the best of our knowledge, were the first electric locomotives built in this country in which a single design of mechanical chassis was used for the installation of the electrical equipment supplied by three different manufacturers, which parts, while not interchangeable with each other, produce a locomotive of practically identical transportation characteristics and of the same mechanical design.

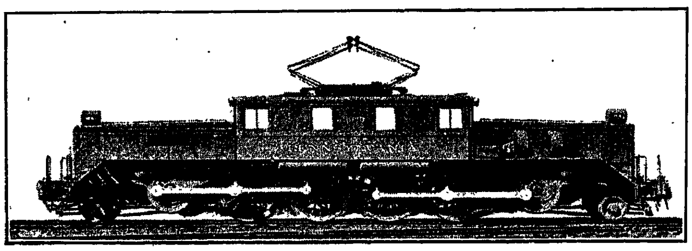

FIG. 1—FOUR DRIVING AXLE GENERAL UTILITY LOCOMOTIVE

Railroad Classification L-5

In these locomotives, by change of gears, it is possible to have either a passenger locomotive for high speed or a freight locomotive for high tractive effort, and by change of type of control with which they are equipped, it is still further possible to utilize them on 600-volt d-c. circuits, or on 11,000-volt a-c. circuits. In other words, by minor modifications in construction, they were designed as a general utility locomotive for use either in passenger or freight service on alternating or direct current.

The study of electric locomotive design has been continuously directed toward the production of a simpler, more easily maintained, and more reliable locomotive. Shortly after the L-5 locomotive was built and placed in service, developments in the design of single-phase motors indicated that a still simpler and sturdier locomotive could be produced. The progress in single-phase motor design has made possible motors of sufficient capacity to handle weights on drivers permitted on the railroad which could be placed between the driving wheels of the locomotive, thus eliminating the necessity for jack shafts and side rods.

It was thought desirable to design some locomotives having these general characteristics and, accordingly, the construction of ten passenger and two freight locomotives was authorized. These locomotives are of three types:

1. A two driving axle passenger locomotive having a four-wheel truck on either end (Railroad classification O-1).

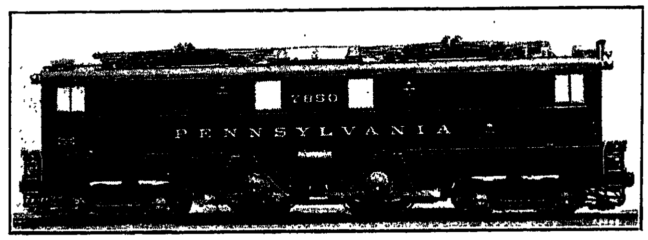

FIG. 2—TWO DRIVING AXLE PASSENGER LOCOMOTIVE

Railroad Classification O-1

2. A three driving axle passenger locomotive having a four-wheel truck on either end (Railroad classification P-5).

3. A four driving axle freight locomotive having a two-wheel truck on either end (Railroad classification L-6).

The passenger locomotives have twin motors of 1,060 hp. each, mounted above each driving axle and driving the wheels with gears and pinions through the medium of the well-known link type drive. The freight locomotive has axle mounted motors of 530 hp. each, driving the wheels through gears and pinions of the same general type of construction as in a street car.

The motors of all the locomotives are identical, the twin motors for the passenger engines being made up of two of the motors of the freight engines. All of the locomotives have roller bearings throughout—in the trucks, in the driving axle journals, and in the motor armature bearings,—the only plain bearings being those on axle to support the motors of the freight engine, and the quill bearings which support the quill in the frame of the twin motors on the passen-

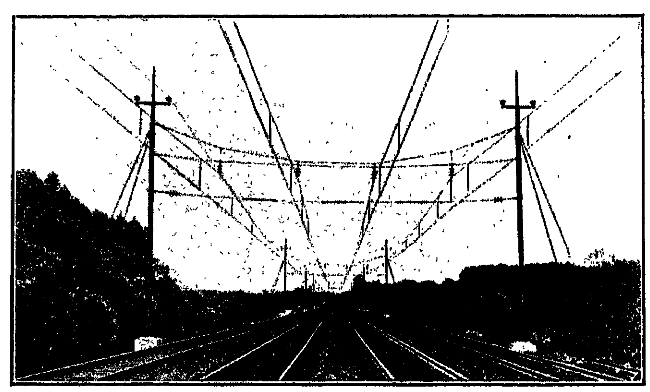

FIG. 3—MAIN LINE CATENARY AND TRANSMISSION LINE CONSTRUCTION

On the Philadelphia Terminal Division between Philadelphia and Paoli

ger engines. The electrical apparatus on the locomotives is interchangeable to a very great extent, the auxiliaries and contactors are identical, and the transformers of the same design though of different capacities. These three types will be the standard until some further advance either in the art or in operating experience indicates further improvement in their design.

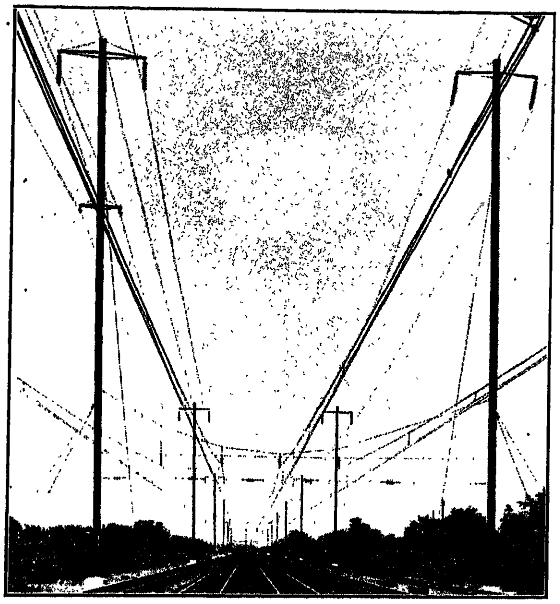

FIG. 4—MAIN LINE CATENARY AND TRANSMISSION LINE CONSTRUCTION

On the New York Division between Trenton and Philadelphia

It might be interesting to note that locomotives of the L-5 and O-1 types were placed on the Locomotive Test Plant at Altoona and were given a thorough period of test to develop the complete operating characteristics before being put into the service. Two of the O-1 type have been completed and placed in service.

While the design and operating experience were in progress on the locomotives, the railroad was active also in developmental work in connection with the circuits for supplying the trains with current.

The initial installation in 1914 provided for 44,000-volt transmission circuits, indoor substations and oil circuit breaker equipment of relatively slow speed. A large part of the overhead catenary construction was of steel and was subject to frequent painting to keep it in condition for service. A brief summary of what has been done to make this layout of substations, transmission lines, and catenary construction, more adaptable to railroad operation, as well as to reduce maintenance costs, is as follows:

On the more recent electrifications, 132,000-volt transmission is used instead of 44,000, thus providing capacity for the transmission of current from one end of a division to another and insuring against shut down due to the loss of any one source of energy.

Substations are now designed as outdoor stations, thus eliminating the major portion of the building with its attendant first cost and cost of maintenance.

Automatic circuit breakers are not used on the 132-kv. circuits, except at junction points where the circuits of one division must, under certain conditions, be automatically separated from those of another.

The trolley circuit breakers on the original installations operated in 12 cycles, including the relay action, and ruptured 30,000 amperes successfully. The modern trolley breakers, however, must operate in one cycle, including the relay action, and rupture 50,000 amperes. One of the electric companies developed an air-break trolley circuit breaker not requiring the use of oil and capable of rupturing currents of the same magnitude and in the same time as the latest oil trolley circuit breakers. We have purchased and installed many of these air breakers and they are giving successful service.

Experience with overhead catenary construction led us to believe that continuity of service secured by the use of non-corrosive materials was of sufficient value in operating reliability to warrant the use of these materials and, accordingly, all of our catenary construction, except parts of material bulk, is of bronze or copper and such bulky pieces are galvanized malleable castings. By this means, painting and other maintenance attention to the overhead catenary system is reduced to a minimum and the continuity of use of track is raised to a maximum, this being of prime importance on a busy railroad.

There has been installed and is being tried out, a length of track with the overhead catenary riveted

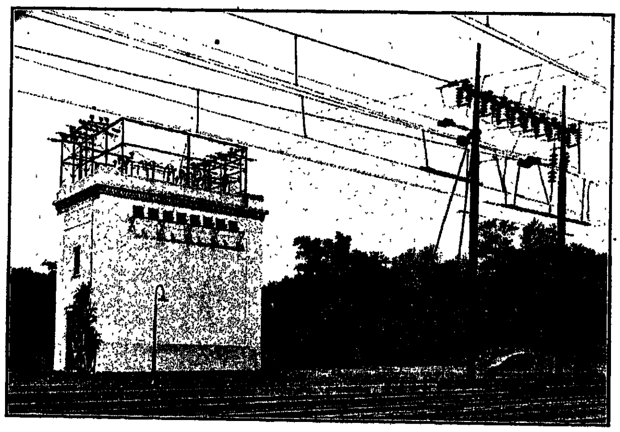

FIG. 5—MAIN LINE 44-KV. SUBSTATION AT BRYN MAWR

Capacity four 2000 kv-a. transformers and necessary switching equipment

instead of bolted together as in the past. This construction gives every evidence of being successful and if this is the case, it will even further materially reduce the amount of attention which the overhead catenary system will require and still further increase the utility of the track beneath it.

A new type of rail bond similar to the well-known signal bonds,—that is, a stranded cable welded or compressed at its ends into plug terminals driven into the rail by a hammer,—has been developed and is used on the Trenton and Norristown electrifications. The use of this bond reduces the initial cost of bonding materially and will, it is believed, reduce bonding maintenance to a minimum.

In conclusion, it may be interesting to indicate some of the questions involved in the actual application of electrification to a railroad after these various points have been considered.

First, an adequate and economical source of power supply must be provided either by providing for the purchase of current, or by designing and building a railroad power plant. This question may be settled largely on economic grounds, as railroad electrifications are now being operated successfully by power supplied from plants designed and built by the railroad companies and that purchased from electric companies.

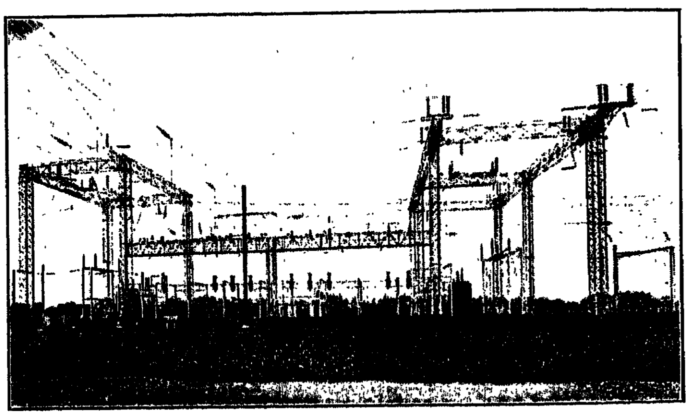

FIG. 6—MAIN LINE 132-KV. SUBSTATION AT EDGELY

Capacity four 4500-kv-a. transformers and necessary switching equipment

Next, it is important to review the real estate situation along the section of railroad to be electrified, so that proper provision may be made for pole location, overhanging wires, and other questions of this character which may affect the placing of supporting structures and transmission circuits along the railroad right-of-way.

Substations are important and sometimes difficult to locate. They must not only be properly placed from the standpoint of voltage regulation, but must also be near a tower so that the apparatus in them may be readily controlled, and at a place where real estate is available or procurable.

A properly systematized working schedule should be prepared showing the beginning and completion of all designs and the dates for placing orders for material and for completion of the work. Items of work which should be completed before the electrification is started, such as the placing of communication circuits and signal power lines underground where this is necessary must be cared for. If this is not necessary, a careful check should be made to see that the poles on which these wires are supported do not interfere with the poles on which the electrification wires are supported and before electrification is started such changes must be made as are necessary to remove physical or electrical interference between them.

Provision of adequate overhead clearance of the trolley wire circuits must be carefully considered and changes made involving the lowering of tracks under highway bridges, or the raising of the bridges, as well as lowering of tracks in tunnels, or at other points where close clearances exist, in order to make room for the trolley wire.

Wires of other ownership crossing the railroad must be considered and the railroad wires erected at such elevations as to interfere to the least extent with these others, or changes made in such crossing wires as may be necessary to clear the railroad circuits.

The signals along the right-of-way must be carefully checked, that their location may coincide with the pole locations for the catenary construction and the changes in these locations confined to a minimum.

The character of signal circuits must also be checked and if necessary changed to properly coordinate them with the traction circuits.

After this preliminary work has been done, the pole foundations may be laid out, the poles designed and purchased, the substation sites prepared and the substation equipment purchased, arranging the dates of delivery of equipment and material in such a way as to meet as nearly as possible the actual erection schedule, thus holding unnecessary interest charges to a minimum.

In this connection, the great advantage of standardizing designs should be pointed out. As an example, if pole spacings can be kept standard, the poles themselves may be standardized, the number of sizes and length of pole reduced to a minimum, the number of sets of catenary hangers also reduced to a minimum and the ease of production and erection materially assisted.

By standardizing pole spacings in terms of catenary hanger spacings, as well as by other means, it has been possible in our electrification work to reduce the number of types of poles used for a given section of track, say of 50 mi., from 150 different types of poles to 15 different types, and from several hundred different sets of catenary hanger lengths to two sets for tangent track and two sets for track of each radius of curvature used.

In addition to the actual application of the electrical circuits and substations to the railroad, the necessary multiple unit cars and locomotives must be purchased upon a schedule which will meet the completion dates of the electrification with as little overlap as possible

and yet with sufficient overlap for safety, again reducing idle investment to a minimum.

This is a necessarily brief description of the electrification program of the Pennsylvania Railroad and the preparation which led up to it, but the work done will show results with the inauguration of the through electrification and will result it is believed in a service of maximum economy and reliability, with comfort to the traveling public.

Discussion

S. Withington: One of the outstanding thoughts which arises in the minds of the readers of Mr. Duer's paper is the large amount of experimental and development work which the Pennsylvania Railroad has accomplished. The magnitude of the installation, by far the most extensive in this country, has justified a great deal of experimentation, and railroads electrifying in the future will obtain much benefit from the investigations carried on by the Pennsylvania engineers. It is of especial interest to note that with its broad background of experience the Railroad's choice should have been the single-phase system of distribution and utilization of power.

One of the outstanding efforts of the Pennsylvania engineers has been the standardization of electric locomotives. This should result in a very considerable saving of expense on account of quantity production, and this saving will be more important as other railroads take advantage of the development, and standardization becomes more general. The economies in quantity production of electric locomotives in many respects are quite analogous to those so thoroughly demonstrated in the automobile industry.

With respect to Mr. Duer's references to substation design, a glance at the illustration indicates the importance which the Pennsylvania engineers attach to a generous allowance of space about oil circuit breakers, transformers and buses. Such spacing undoubtedly brings about maximum reliability and tends to localize any failures which may occur. If the substations can be located where land is relatively inexpensive, the logic of this arrangement is especially obvious.

Mr. Duer suggests that substations should be located near a signal tower so that the circuit breakers may be readily controlled. On account of the growing practicability of remote-control facilities this is not now as important as it was formerly, but it is of primary importance to locate the trolley wire sectionalizing points and circuit breakers where there are crossovers between tracks so that in the event of abnormal conditions, trains may be crossed from one track to another to run by the sections where there may be trouble.

Regarding the use of non-corrosive materials, this is a notable development of electrification installations in recent years, and is an excellent example of the kind of lessons which are being learned through experience.

The rail bonds adopted for the Pennsylvania electrification are a somewhat radical departure from previous standards, and it will be interesting to note the performance on this very heavy section of route.

Mr. Duer's reference to the source of power is of interest. He points out that the question of decision as between purchase and manufacture of power is largely economic. All railroads which contemplate electrification are of course faced with this important question very early. The development of larger and more efficient central stations and the economies of interconnection of power systems are paralleled by the growing efficiencies of smaller plants, and both the railroads and the power companies must figure very closely to arrive at a satisfactory solution. One of the important items for consideration in figuring costs of power may be the high rate which power companies sometimes assume as interest on the capital represented by their power plants and associated facilities, which is often considerably more than the railroads can justify for their own facilities. A relatively small difference in these assumed percentage figures may be sufficient to swing the decision one way or the other.

In connection with preparations which are necessary for electrification, Mr. Duer has indicated a number of points which must be considered, but he has not mentioned the desirability of completing any general improvements such as the elimination of grade crossings, straightening tracks or lengthening curves. Changes of this nature should be completed, so far as they can be foreseen, before the installation of catenary construction, because the difficulties of any changes which are made after electrification has been completed are of course considerably greater than before.

The standardization of detail parts for catenary construction is extremely important, and general agreement in such design among electrified railroads is one of the items which will advance electrification as much as any other single question.

T. A. Purton: In general, what special measures were required to prevent telephone and communication interference?

K. V. B. Duer: In reply to Mr. Purton's question, it may be said that no special measures were required to prevent telephone and communication interference. Electric-traction circuits were very carefully designed and laid out for the best results from an electric-traction standpoint, and operating experience so far has indicated that no modifications in these circuits were necessary to take care of telephone and communication interference.

Electricity's Part in Open Cut Copper Mining

BY R. J. CORFIELD[1]
Associate, A. I. E. E.

Synopsis.—*This paper is intended to describe the electrification of the world's largest open cut copper mine, and also covers briefly main line transportation and miscellaneous uses of electrical energy at the concentrating plants, that are located approximately 18 miles from the mine.*

This electrification project was an economical and progressive step in copper mining and developed some very interesting engineering problems.

Electric shovels, both alternating and direct current, together with the special type of electrical locomotive required for this particular service, are discussed.

The rather elaborate trolley and feeder system required to transmit power to a fleet of 23 electric shovels and 39 electric locomotives, scattered over a 725-acre area, is described.

The main power system, together with mill, railway and shovel substations, is briefly described.

Some operating statistics are given, to assist in visualizing the magnitude of the operations.

THE Utah Copper Mine is in reality a mountain of low grade copper ore, covered by an overburden of decomposed rock, varying in depth from 75 to 200 ft. The clearly defined levels, or benches, as shown in Fig. 1 vary in height from 70 to 130 ft. and have a slope of approximately 45 degrees. Some of the levels are very narrow at the ends and gradually widen towards the center. The ore, after being blasted from the banks and loaded, is transported to the main assembly yard over a series of switchbacks, built in most cases with an average grade of 4 per cent.

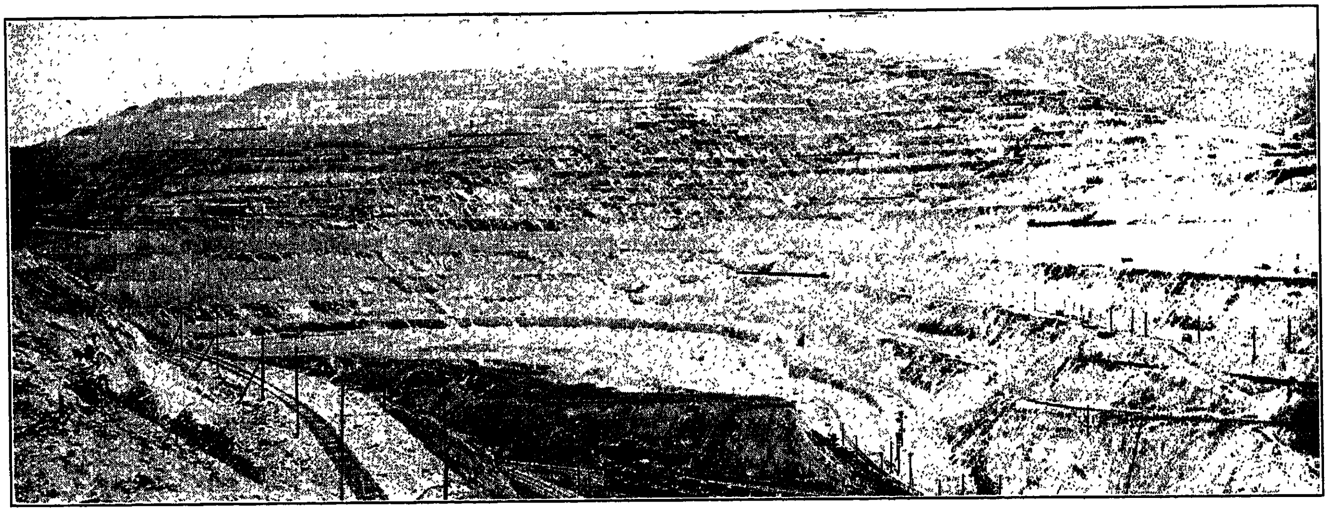

FIG. 1—GENERAL VIEW OF MINE

Fig. 2 is a map showing a part of the haulage system. Both the ore and waste break rather easily and the blasted material varies from gravel size to very large boulders which, if too large to go in the dipper, have to be separately blasted before loading. The material in its blasted condition, ready for loading, weighs approximately 4160 lb. per cu. yd.

TYPES OF LOADING EQUIPMENT

The first steam shovel was put in operation in 1906, and more were added as conditions warranted. The original shovels were equipped with railway type trucks and 2½ cu. yd. dippers. These dippers were later replaced by 3¼-yd. dippers and some caterpillars were installed. Later all steam shovels were equipped with 4½-yd. dippers and caterpillar tractors.

The first electric shovel appeared in 1922 at which time two, Marion Model 92, were purchased, both being equipped with caterpillar tractors and 4½-yd. dippers.

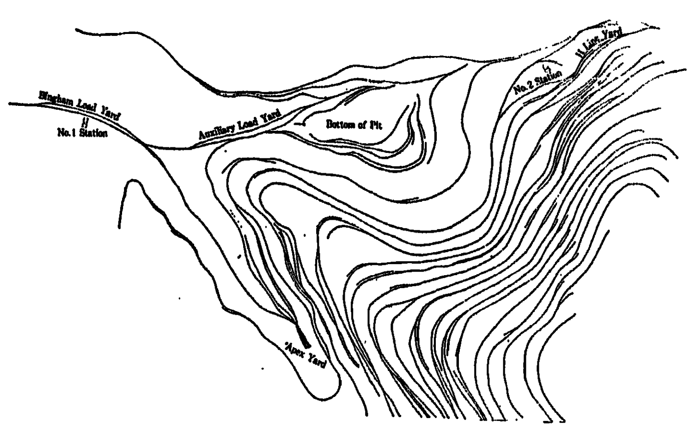

FIG. 2—PART OF HAULAGE SYSTEM

1. Asst. Elec. Eng., Utah Copper Co., Garfield, Utah.

Presented at the Pacific Coast Convention of the A. I. E. E., Portland, Oregon, September 2-5, 1930.

One of these shovels was driven by d-c. motors while the other was equipped with a-c. motors. Rather extensive tests, both electrical and capacity, were made and both of these shovels proved to be far superior to steam shovels, considerable increase in economy being shown,

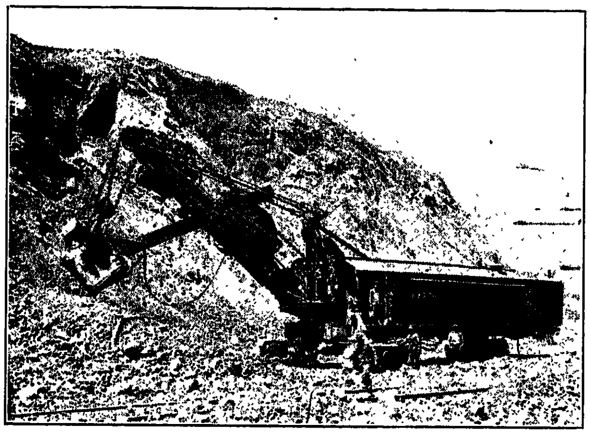

Fig. 3—Electric Shovel

together with a great many operating advantages that could not be capitalized. In 1923, eight additional shovel equipments, using a-c. motors were ordered, and eight shovels were converted from steam to electric drive. After these shovels had been in operation sufficient time to prove their superior operating economies, other shovel equipments were ordered until at the present time there are 23 electrics operating and no steamers. Nine of these shovels are equipped with a-c. motors, with rheostatic control, and fourteen with d-c. motors using the Ward-Leonard system of control, modified to meet the particular kind of service, which is

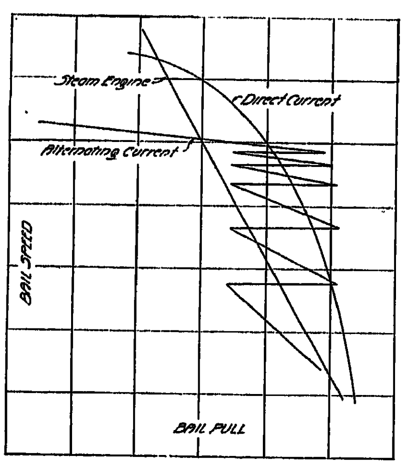

Fig. 4—Comparative Shovel Characteristics

very severe and requires the most sturdy motors and control equipment. Fig. 3 is a view of a modern electric shovel.

Shovel Characteristics

The electric shovel was primarily designed to replace the steam shovel which, with the exception of its poor economy and high maintenance, has an ideal control characteristic, and an electric shovel should therefore be designed with a type of control that will duplicate the steam characteristic as nearly as possible. A curve showing the comparative characteristics of steam, alternating current, and direct current drive, is shown in Fig. 4, and it should be noted that the Ward-Leonard system of control approaches very closely to the steam characteristic, giving the necessary smoothness and flexibility.

Three types of d-c. motors are available for shovel drive, *i. e.*, shunt, compound, or series wound.

Which of these motors is best adapted for shovel drive depends on the nature of the material handled

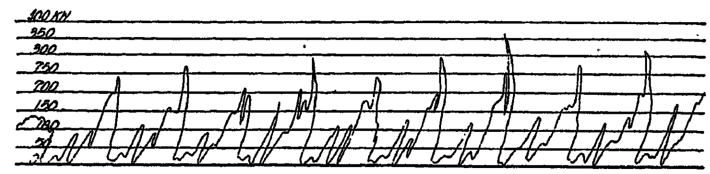

Fig. 5—Power Input Curve, D-C. Equipment

and speed requirements. In general, it may be said that the separately excited, differentially compound wound generator, supplying power to series wound hoist motors and shunt wound swing and thrust motors is best suited for general application to railway type shovels. Typical graphic charts showing the power required, peaks, and general character of the duty cycle, are shown in Fig. 5, for the d-c. equipment, while Fig. 6 shows the corresponding curves for the a-c. equipment. These curves are intended to be typical and not comparative, as a number of almost impossible conditions must be realized before comparative curves can be made, *i. e.*, character of

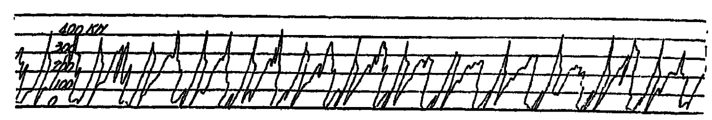

Fig. 6—Power Input Curve, A-C. Equipment

material, personnel of crew, and condition of equipment must all be equal. These curves indicate the severity of the duty cycle and show clearly the necessity for using the most substantial type of electrical equipment available. It should also be noted at this point that the electrification of shovels has been directly responsible for an improved mechanical shovel, as the torques obtained from the electric motors are greater than from steam engines, making it necessary to strengthen the underframing, gearing and other structural parts of the shovel. This increased strength and sturdiness means fewer mechanical delays and is, therefore, a contributing factor in electrification economies.

Electrification has also fostered a close relationship between the shovel manufacturer and the electrical equipment manufacturer, with the result that the electric shovel in its present form is a highly co-ordinated and well arranged piece of equipment. The shovel operator has also had an important part in this development in suggesting certain changes in both mechanical and electrical equipment. Tests, extending over a period of years, are necessary before practical conclusions can be drawn. During this period, power costs, tonnage loaded, repairs and operating time must be tabulated. Such a tabulation, showing comparative operating costs of electric and steam shovels, is shown in Table I. About one-half of the saving shown is due to

TABLE I—PROPORTIONATE COST PER TON LOADED

Steam		Electric	
Engineer	100	Engineer	100
Craneman	100	Craneman	100
Fireman	100	Electrician	51.1
Coalman	100	Electrician's Helper	51.8
Pitman	100	Pitman	100
Watchman	100	Watchman	0
Total Operating Labor	100	Total Operating Labor	76.2
Coal and Water	100	Power	17.5
Packing and Oil	100	Packing and Oil	34.0
Total Operating Material	100	Total Operating Material	20.4
Repairs	100	Repairs	21.5
Total Cost Per Ton	100	Total Cost Per Ton	37.2

electrification, while the other half is due to the substitution of caterpillar traction for railway trucks. It should be noted that the tabulation does not include fixed charges on either type of equipment, and while it is hardly expected that the electric drive will ever be as low as steam in first cost, economies and other advantages outweigh the advantage of steam in this respect.

LOADING CAPACITY

The electric shovel is capable of loading more ore per shift than its steam competitor, due to the fact that it is practically impossible to keep up uniform steam pressure. Delays due to leaking steam and water lines, choked boilers, etc., also contribute. Individual cycles timed by stop watch show the steam shovel to be just as fast and in some cases faster than the electric, but the fast cycle cannot be repeated over the days work, for the reasons outlined above. On the other hand, the present electric shovel is a highly developed and simplified machine, and while electrical delays occur, they are usually due to control equipment and can be repaired very quickly, and in a great many cases are of such a nature as not seriously to affect the operation of the shovel, and can be left until the shift is completed. The loading capacity of the electric is roughly 14 tons per minute, and if cars were available and there were no delays, it would be possible to load 6,720 tons per shovel shift, or a total tonnage of 154,560 tons with 23 shovels. However, as the operating time factor averages about 80 per cent, and as cars are not always available, this tonnage is reduced to about 105,000 tons maximum per day.

The ore tonnage varies from 35,000 to 50,000 tons per day, while the waste tonnage varies with the mine development. The ore, after being loaded, must be transported to various assembly yards, while the waste must be dumped in adjacent ravines. This work is performed by 39 electric locomotives, designed especially for the service. Due to the complexity of trackage, it was not considered practical to string trolley over all tracks and there were certain places, particularly on the benches, where trolley could not be placed over the center of the track. To obtain maximum operating range, the locomotives were equipped with a standard pantograph, two side arm collectors and a cable reel and, in some cases, a 680-ampere hour storage battery was used in conjunction with the regular collecting devices. Fig. 7 is a view of a typical electric locomotive, while Table II is a

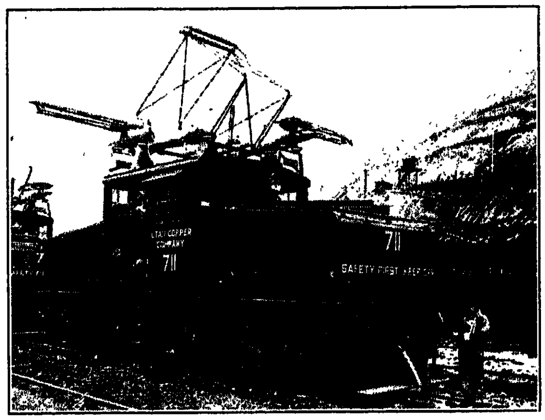

FIG. 7—TYPICAL ELECTRIC LOCOMOTIVE

TABLE II—LOCOMOTIVE SPECIFICATIONS

Rigid Wheel Base	8 ft.-0 in.
Total Wheel Base	25 ft.-2 in.
Wheel Diameter	44 in.
Length Inside Knuckles	36 ft.-6 in.
Weight	154,000 lb.
Compressor Capacity	150 cu. ft.
Motor Rating (One Hour)	261 Hp. at 105 deg. cent.
Gear Ratio	85 : 18
Rail Clearance	4⅜ in.

condensed specification covering a standard locomotive. These locomotives will haul a trailing load of 250 tons up a 4 per cent grade at a speed of 10 mi. per hr., with a power input of approximately 825 kw. Motors are totally enclosed and have a one hour rating of 280 amperes, giving a tractive effort of 35,000 lb. The continuous rating is 120 amperes, corresponding to a tractive effort of 11,200 lb.

TROLLEY SYSTEM

The design of an adequate trolley system to serve the

locomotives required considerable study, as there were many limitations imposed by the operating department. The first problem was that all poles had to be placed on the bank side of the track, in order that ditching and spreading operations could be carried on. This problem was solved by using extra long bracket arms and placing the pull-over backbone on the end, as indicated in Fig. 8. A large number of waste fills, varying in height from

Fig. 8—Trolley Construction on Switchbacks

100 to 250 ft., had to be electrified, and as these fills will settle approximately 10 per cent of their height, it was necessary to use a construction as shown in Fig. 9, where the pole is made a part of the track structure by means of extended ties. A number of bridges, on curves varying from 12 to 24 deg., was taken care of by a light "I" beam structure as shown in Fig. 10. On the benches, the track is moved every 25 days and some kind of portable structure was required. It was also

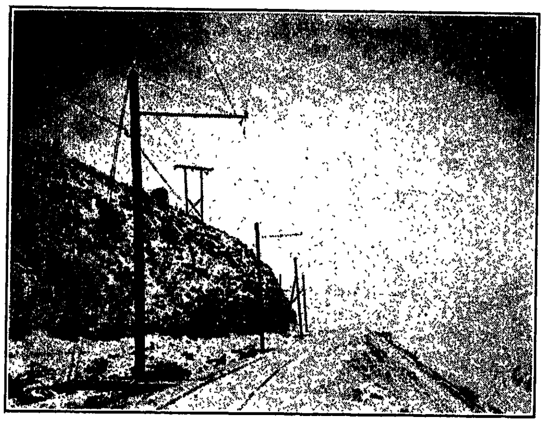

Fig. 9—Trolley Construction on Waste Fills

necessary to have a portable shovel line on the bench. A light steel tower, as shown in Fig. 11, was designed to take care of both lines. These towers are 25 ft. high and weigh approximately 900 lb. They are provided with heavy skids on the bottom for sliding, or may be picked up by a locomotive crane. Despite the fact that these structures are within the blasting zone, very little trouble has been experienced. All overhead construction is of the direct suspension type, with the exception of the Bingham Yard, which is catenary.

Main Line Transportation

The ore is taken from the assembly yards at the mine and transported 18 miles to the milling plants for concentration. This work is done by seven Mallet locomotives, weighing 316 tons each. The main line

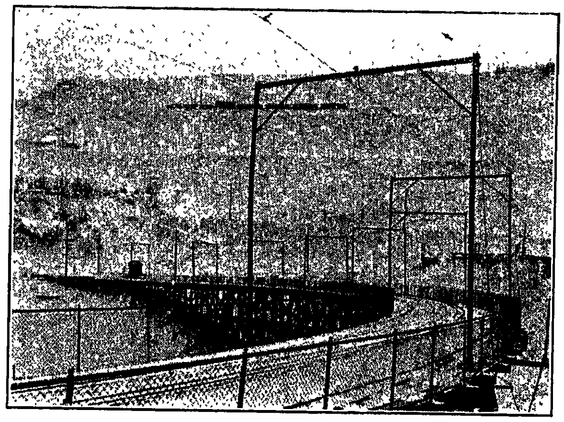

Fig. 10—Trolley Construction on Bridges

railroad is single track, with six passing sidings, the Bingham end passing through four tunnels, bored into solid rock, and having an aggregate length of approximately one mile. For years this railroad operated without any signaling devices, and the train crews were directed by train orders from the dispatcher, and while

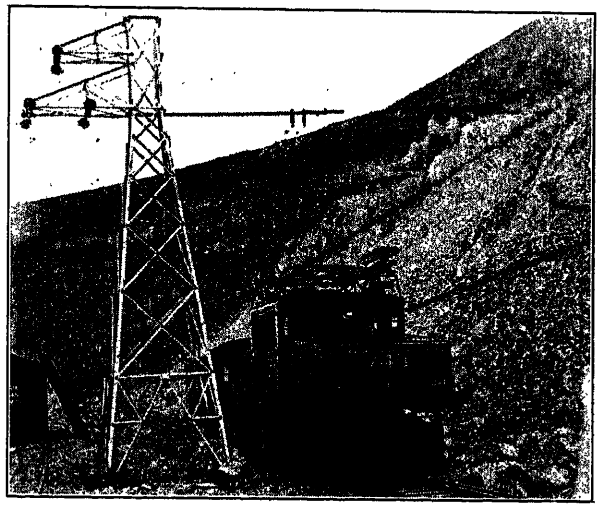

Fig. 11—Trolley Construction on Benches

these dispatchers were very proficient in making train meets, it was known that more efficient operation could be realized with the road properly signaled. Accordingly, for the purpose of study, the tunnel section was protected with automatic signals and two switches were equipped with remote control. The value of signals and remote-controlled switches was soon recognized and resulted in complete signaling of the road, as well as

the Magna Yards. Train orders were, however, still necessary as no superiority could be established between uphill and downhill trains.

In 1925, a system of centralized traffic control was developed whereby the dispatcher controlled the siding signals, thus giving him complete control of all trains without the necessity of train orders. This system was installed on the railroad in 1929, and has resulted in a marked saving in running time in addition to the natural safety features inherent in signal systems. Fig. 12 shows signals at a typical siding, while Fig. 13 shows the dispatcher at work.

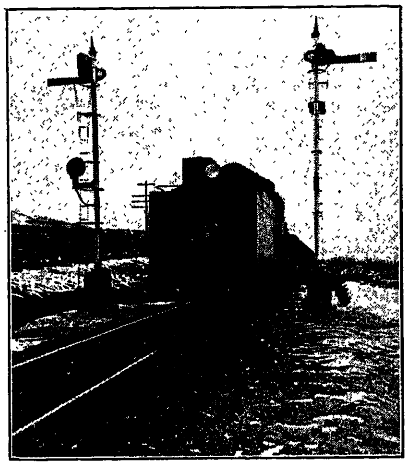

FIG. 12—SIGNALS AT TYPICAL SIDING

At the mill yards, electric locomotives break up the 50-car train from the mine into 10 car cuts, ready to be dumped. This service was formerly performed by a steam switcher, and due to the rather erratic demands at the car dumpers, this engine was on spot about 50 per cent of the time, resulting in a high dumping cost per car. The ore, after being dumped, is given a primary crushing, a secondary crushing, preliminary and final grinding, to reduce to minus 100 mesh. From these mills the slime is conveyed to the flotation plant where the ore and gangue are separated. After being dewatered, the concentrate is ready for shipment to the smelter for preliminary refining. The mill work is done by motors varying in size from one-quarter to 850 hp. most of them being of the standard, squirrel-cage, induction type. Synchronous motors are used wherever possible, and all new drives are carefully considered with the idea of using synchronous instead of induction motors. All motors are started across the line at 440 volts, and in the majority of cases with contactors designed and built by the company's forces. Miscellaneous uses about the plants include electric rivet heaters, hot plates, water and acid heating, pipe annealing, floodlighting, etc. All new motors are purchased with anti-friction bearings, and the conversion of sleeve to anti-friction bearings has been going on for several years, the end bells and caps being designed by the engineering department and these parts cast and finished in the company's foundry and machine shops.

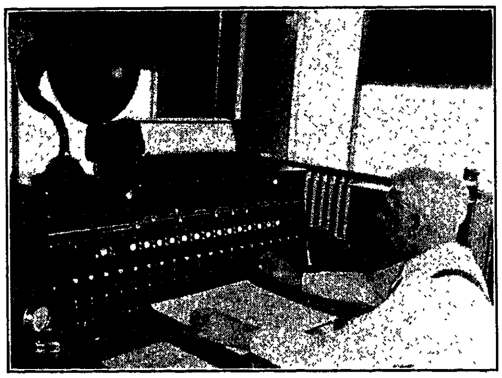

FIG. 13—TRAIN DISPATCHER AT WORK

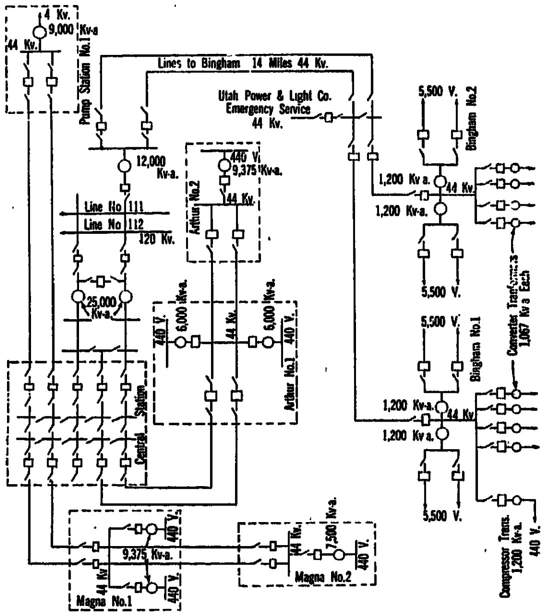

FIG. 14—LINE DIAGRAM OF POWER SYSTEM

POWER SUPPLY

Power for these operations is furnished by the Utah Power & Light Company and is received at Magna Central Station at 120,000 volts, where it is stepped down to 44,000 volts and distributed to seven substations. Fig. 14 is a single line diagram of the system. This central station has an installed capacity of 62,000 kv-a., divided into three transformer banks, two 25,000-kv-a. banks for the mills, and one 12,000-kv-a. bank for the mine. All 120,000-volt apparatus is installed outdoors, while the 44,000-volt switches and control equipment is indoors. Figs. 15, 16, and 17 are views of this station.

As continuity of service is a very important consideration in an industry of this kind, duplicate lines are carried to each substation and ring buses are used to gain switching flexibility. Each mill substation is provided with a spare transformer, so arranged that it may be used to spare any one of the bank with a mini-

mum delay. Power at 440 volts is transmitted through three conductor cables direct to the motors, or to suitable buses, each circuit being protected by an oil circuit breaker and suitable relays. A typical mill substation is shown in Fig. 18. Power is transmitted

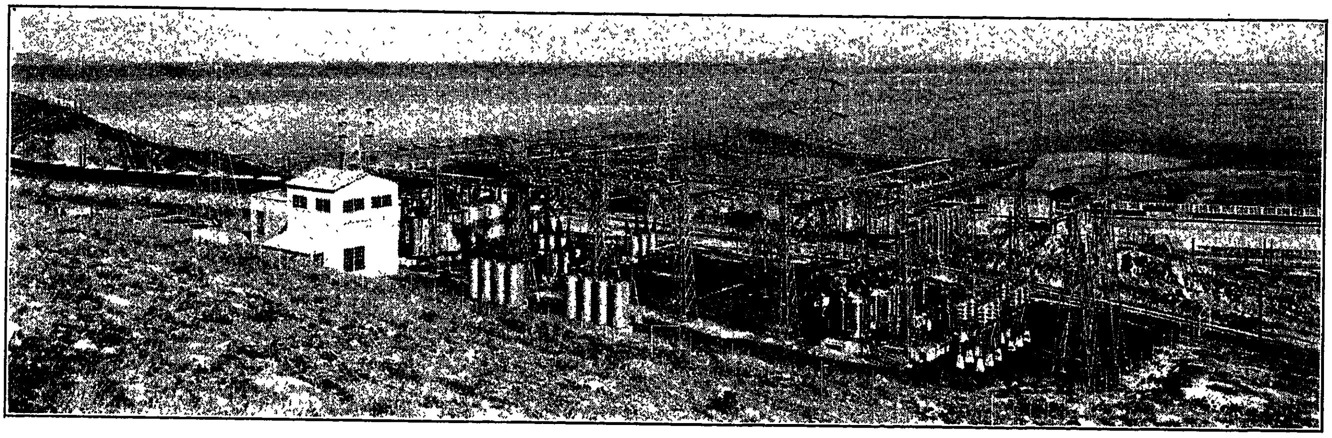

Fig. 15—General View of Central Station

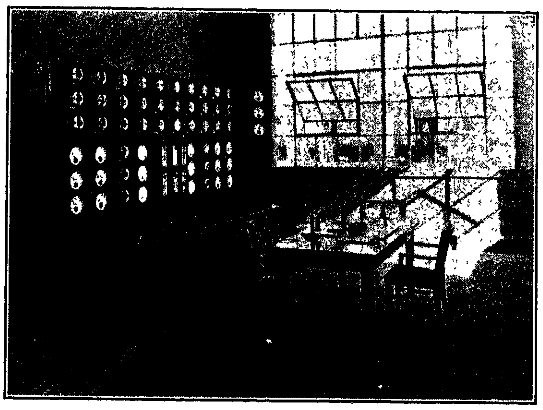

Fig. 16—Control Room

Fig. 17—Interior of Station

to Bingham over a two-circuit tower line and distributed to two, composite, shovel and railway substations. (Fig. 19.) Each shovel substation, which is of the outdoor type, contains two banks of transformers, rated at 1200 kv-a. each, the secondary voltage being 5500 volts.

This energy is carried over two independent pole lines arranged to completely encircle the mining area, and built to approach as closely as possible the ends of the benches, where they are tapped and run through a portable switch house containing an automatic oil

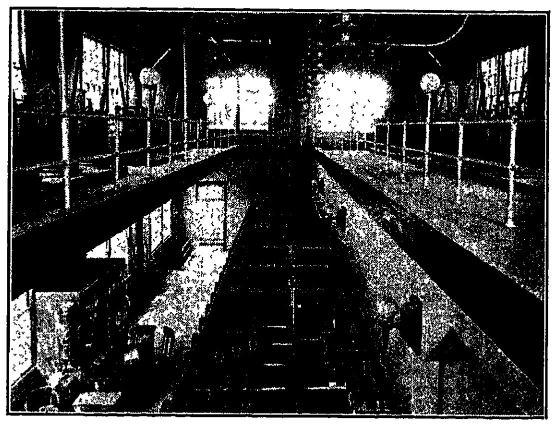

Fig. 18—Typical Mill Substation

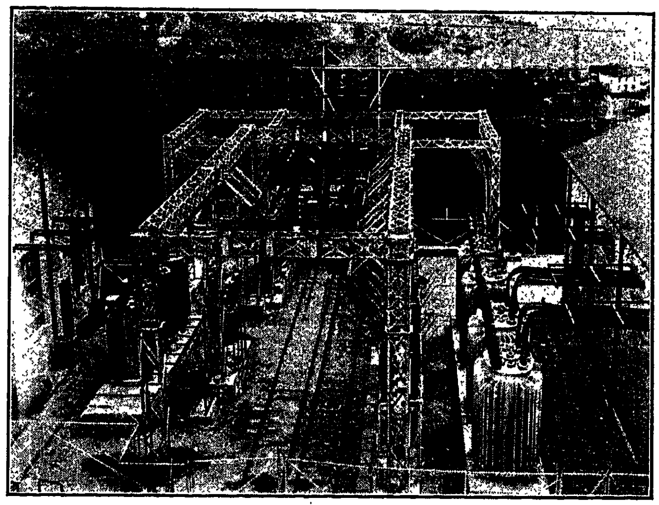

Fig. 19—General View of Shovel and Railway Stations

circuit breaker. From this point they are carried across the bench on the portable towers before mentioned. With this system it is possible to feed the shovel from

any one of four secondary trunk lines. Such a distribution system may seem rather elaborate, but when it is considered that a large fleet of shovels would be delayed in case of line failure, such a system is warranted.

The railway substations are of the semi-outdoor type and are full automatic. The 44,000-volt oil circuit breakers and converter transformers are outside, while the converters and auxiliaries are inside. Each station (Fig. 20) contains four, 1,000-kw., 750-volt, 1,200 rev. per. min., shunt wound converters, all tied to a common bus from which eight feeder circuits are taken. As the speed of the locomotives is directly proportional to the trolley voltage, it is important that adequate feeders be provided, and also that the trolley system be properly sectionalized so that an interruption on one feeder does not affect a large number of locomotives. The feeder system at Bingham is so arranged that six locomotives, operating on three levels, are supplied from two sources over two separate feeders. As faults are most likely to occur on the benches, this arrangement

FIG. 20—INTERIOR OF AUTOMATIC RAILWAY STATION

permits operation up to the bench where sectional switches are provided for switching to a good feeder. The magnitude of these operations may be more easily visualized by consulting the following statistics, representative of one year's operation.

Tons of ore loaded	16,556,070
Tons of waste loaded	14,400,170
Total tons of material loaded	30,956,240
Tons of ore hauled by electric locomotives	16,031,728
Tons of waste hauled by electric locomotives	5,465,939
Total tons of material hauled by electric locomotives	21,497,664
Total kilowatt hours used by electric shovels	6,190,136
Total kilowatt hours used by electric locomotives	7,536,604
Total kilowatt hours used by Utah Copper Company	323,454,428
Average yearly load	36924 kw.
Maximum load for year	45155 kw.
Annual load factor	81.8%

Discussion

L. W. Birch: During 1924 the Utah Copper Company replaced two steam switching locomotives in the Magna-Arthur crusher yards, with two 75-ton electric locomotives. These locomotives were equivalent in weight to the replaced steam locomotives. The crusher yards include seven miles of track and are used for handling ore cars at the two mills where the ore is crushed previous to its treatment in the flotation plants. Approximately 600 cars of ore have been handled per day through these yards during the past six years.

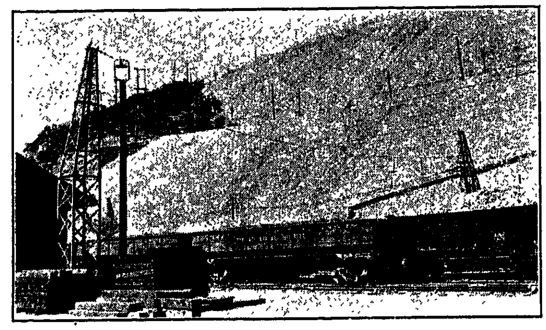

FIG. 1—CATENARY AT BINGHAM MINES 1930

The distribution and collection system on this electrification consists of light catenary with normal tangent spacing of 150 ft. A 7/16-in. steel messenger wire, supporting a 4/0 grooved hard-drawn copper contact wire, was used throughout the system. Flexible steel catenary hangers connect contact wire and messenger wire. This system was insulated for 600 volts d-c. and is operating at that voltage at the present time, energy being obtained from a central substation located at the company's large distribution substation at Magna, Utah.

A recent check of this system has indicated very little maintenance and extremely minute wear on the contact wire. Initial costs in connection with the insulation were reasonable and were

FIG. 2—CATENARY AT BINGHAM MINES 1930

completely written off through the savings obtained by elimination of steam after the first eighteen months of operation. Through the favorable operation of this section, it was decided to build catenary in the yards at the Bingham mines. This is mentioned in Mr. Corfield's paper and is illustrated in two of the attached illustrations. This light type of catenary is suspended mostly by steel structures, the structures being of the bolted type and erected on the ground.

In designing and constructing the overhead system at the Bingham mines, considerable thought was given to the flexibility of the overhead system. Wherever possible the flexible overhead system was constructed in lieu of the rigid system. Photographs

indicated as Figs. 8, 9, and 10 in Mr. Corfield's paper, illustrate how flexibility was built into this system. For instance, the contact wire in Figs. 9 and 10 is suspended by a piece of flexible cable passing over a porcelain insulator and attached to the contact wire by half strain ears. A flexibility is obtained in this way which reduces trolley wire wear and breakage at the suspension point.

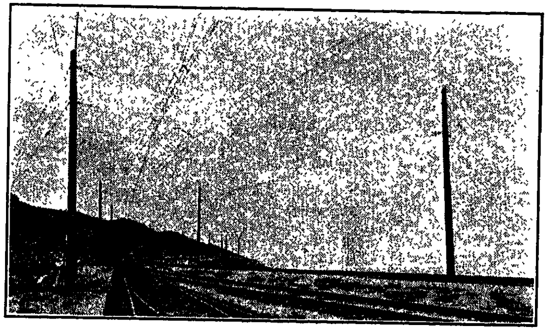

FIG. 3—MAGNA-ARTHUR CRUSHER YARDS ELECTRIFIED 1924

This flexible arrangement was also installed on some of the original stripping tracks on the benches. Owing to complications in moving the portable towers and to the occasional breakage due to blasting, it was thought that a more simplified system, even though it included rigid suspension points, would be advisable. As an outcome the portable structures on the benches are now equipped with a standard type of insulated mine hanger to which is attached a standard type of mechanical mine clamp. This mine clamp has an opening above the jaws into which the trolley wire can be inserted and held loosely while the towers are being moved. In this manner the shifting of track and towers is accomplished without much work, and

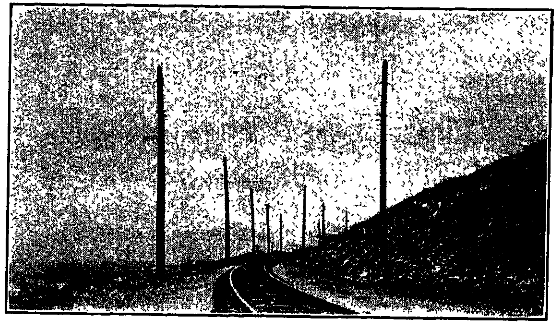

FIG. 4—ANOTHER VIEW OF YARDS ELECTRIFIED 1924

the contact wire can be held in a position above ground without injury. After the towers are moved, the contact wire is taken out of this opening in the clamp and placed in the regular jaws of the clamps, the wire having been tensioned previous to the clamping.

Hydraulic and Electrical Possibilities of High-Speed, Low-Head Developments

BY GEORGE A. JESSOP[1] and C. A. POWEL[2]
Member, A. I. E. E. Member, A. I. E. E.

Synopsis.—The paper deals with the change brought about in hydroelectric practise by the introduction of the high-speed low-head propeller type of turbine. For a given head, up to about 70 ft., it is possible to run the units at a much higher speed, thus reducing materially the cost of the generator. The maximum efficiency of the unit is maintained and the part load efficiency greatly improved by the use of adjustable blade turbines, so that there is also a material gain where variable load or flow is to be handled. The fundamentals underlying the design of an adjustable blade propeller type turbine are given and an illustrative study made of a three-unit station, to show the gain in output obtainable from this type of unit.

BECAUSE of economy in first costs, a great deal of effort has been expended, for the past twenty years, to secure higher speed hydroelectric units. The principal reduction in first cost has been due to the lower price of the generator equipment as the speed increases, the hydraulic turbine costs decreasing to a less extent. Until recently the increase in speed has resulted in reduction of efficiency, particularly at part loads, thus to a large extent offsetting the advantages of reduced investment. The improvement in generator efficiency with increased speed has only partially offset the reduced turbine efficiencies. Turbine designers have now succeeded in maintaining the maximum, or peak, efficiency at a given figure over a very wide range of specific speed, and by means of the Kaplan, or automatically adjustable blade runner, have improved the part load efficiency far above that formerly obtained even with slow-speed Francis turbines.

The hydraulic turbine horsepower and efficiency data and information contained herein have been obtained from tests made in the field and in specially designed and constructed testing flumes. The relationship between head, power and speed given in Fig. 4 has been checked by numerous actual installations, and for the axial flow turbines, further investigations have been made recently by means of cavitation tests. In determining specific speed the well known formula

$$N_s = \frac{RPM\sqrt{HP}}{H^{\frac{5}{4}}}$$

has been used. For slide rule computation this is, perhaps, more conveniently used in the form $N_s = \dfrac{RPM}{H}\sqrt{\dfrac{HP}{\sqrt{H}}}$. The specific speed of a runner is the rev. per min. at which a homologous runner will operate under one-ft. head when it is so reduced in size as to develop one hp. under one-ft. head.

Fig. 1 shows the relationship between specific speed and maximum efficiency. Generally speaking, Francis turbines are used up to a specific speed of 110 and the adjustable and fixed blade propellers for specific speeds above this figure. It will be seen that very high specific speeds can be used before any material reduction in maximum efficiency is suffered.

Fig. 2 shows a comparison between the peak and part load efficiency of turbines with specific speeds ranging from 25 to 150. The turbines with specific speeds of 25, 50, 75 and 105 are Francis turbines. Of the two turbines with a specific speed of 150, one is of the fixed blade and the other of the adjustable blade axial flow type. It is interesting to note how

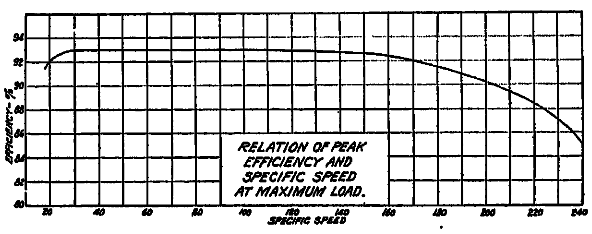

FIG. 1—RELATIONSHIP BETWEEN SPECIFIC SPEED AND MAXIMUM EFFICIENCY

the part load efficiency drops off very rapidly as the specific speed is increased—a defect which can be overcome by the use of the adjustable blade turbine. The notable feature of this latter type is the fact that the efficiency over the entire range of output is very high, exceeding even that of the lowest speed Francis turbine at low loads.

Fig. 3 shows how the efficiency of the generator varies with the load. It will be noted that the efficiency increases with the size of the unit and also with speed. The part load efficiency increases less rapidly than the full load efficiency, because of the more marked effect of the windage losses at the higher speeds. Data similar to that given by Figs. 2 and 3 must be combined to obtain the performance of the complete unit.

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Presented at the Middle Eastern District Meeting No. 2, of the A. I. E. E., Philadelphia, Pa., October 13-15, 1930.

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Fig. 4 makes available graphically a method for determining the allowable relationship between head, horsepower, and speed. The head curves represented by full lines are to be used for Francis turbines, and those represented by dotted lines for axial flow turbines. At the upper left hand, part of the chart lines have been drawn indicating approximately the limits

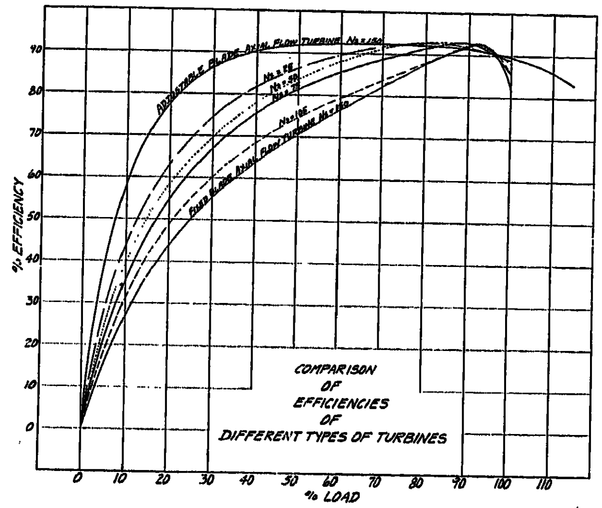

Fig. 2—Comparison Between Peak and Part Load Efficiency of Turbines with Specific Speeds Ranging from 25 to 150

of capacity corresponding with the different heads. It is believed this information will be very useful for preliminary engineering work in connection with the designing and estimating of hydroelectric developments and the selection of suitable generator speeds. The limitations of specific speed—that is, the combination of horsepower, head, and speed—set by this chart

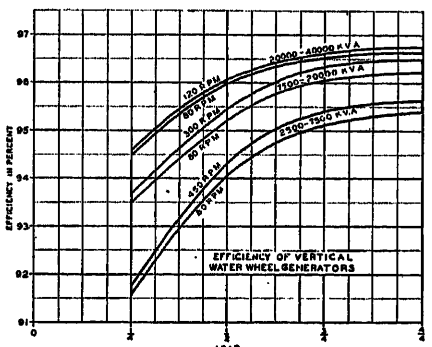

Fig. 3—Shows Variations in Generator Efficiency with Load and Speed (Three-Phase 80 Per Cent Power Factor, 60 Cycles)

are the results of many years of experience and may be regarded as good practise at the present state of the art. If plants are designed within these limits and with the proper relationship between the center line of the unit and tailwater, best results in output, economy and long life are secured.

The field of application of the fixed and adjustable blade axial flow turbine lies in relatively low-head developments, approximately 70 ft. or less. One of their great advantages is that they permit of considerably higher speeds than the older Francis turbine, so that today it is permissible to speak of "high-speed low-head" units.

The effect of speed on the first cost of the turbine is comparatively slight, but there is a definite trend towards reduction in cost with increase in speed. The rev. per min. of a fixed blade axial flow turbine may be about 70 to 80 per cent higher than that of a medium speed Francis turbine, and, very approximately, the reduction in cost about 5 to 10 per cent. The reason for the small reduction in cost lies in the fact that the amount of water to be handled is the same in either case and the same water control mechanism is required surrounding the runner. The small saving is the result of handling the water at somewhat higher velocities

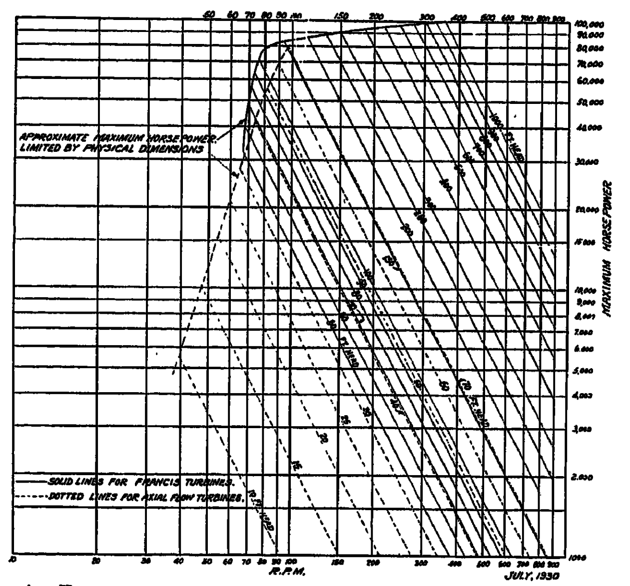

Fig. 4—Relationship Between Head, Horsepower and Speed of Francis and Axial Flow Turbines

and, therefore, with somewhat less cross-sectional areas, and greater simplicity of runner design.

From the generator designers' point of view, there is always an advantage in increasing the speed. With increased speed, the cost of the generator goes down and the efficiency goes up. Fig. 5 shows how the cost of water-wheel generators varies with capacity and speed. The curves are drawn upon the basis of normal overspeeds, that is, 100 per cent for generators up to 200 rev. per min. and 85 per cent above that speed. When the unit speed can be selected with a view of obtaining suitable efficiency at or n ar the maximum head, the overspeed of axial flow turbines is usually double the normal speed. For plants having a head that varies through a large range when it may be desirable to select a speed suitable for a head considerably under the maximum, the overspeed may be more than double normal, and special provision must be

made in the generator design. For the higher ranges of heads suitable for axial flow turbines, when it is desirable to set the turbine as high as possible with respect to tailwater, the overspeed is frequently reduced by cavitation.

The cost of an automatically adjustable turbine is

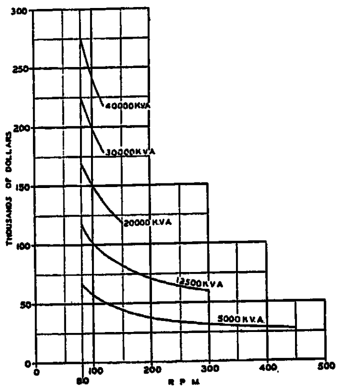

FIG. 5—SHOWS VARIATIONS IN GENERATOR COSTS WITH CAPACITY AND SPEED

substantially greater than that of a fixed blade turbine. The increase in cost varies from about 20 to 25 per cent for very large sizes to as much as 50 per cent for small sizes. This type shows a marked in-

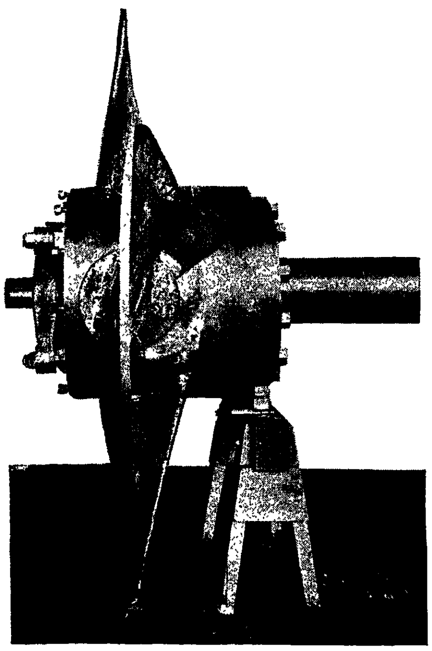

FIG. 6—AXIAL FLOW TURBINE WHEEL WITH ADJUSTABLE BLADES—CLOSED POSITION

crease in kilowatt-hour output and, therefore, in earnings. Since the cost of the turbine is, in almost every development, but a small fraction of the whole cost, the total investment is increased only a small percentage.

There are other factors to be considered, such as excavation and power house cost. Turbines of high specific speed, in general, will be set at a lower elevation than those of low specific speed, thus tending to increase excavation cost. This tendency is counter-balanced to some extent, because the water flowing through high specific speed turbines is handled at slightly higher velocities and the length of the power house may be decreased, resulting in a saving in superstructure. Each development must be worked up as an individual problem. It is believed that for every installation the increased earnings will more than amply compensate for the greater investment involved.

Kaplan turbine runners, both of the fixed and automatically adjustable types, have a totally different form from Francis turbine runners. In the former, a few wing-like runner vanes, or buckets, without the familiar rim around their outer ends, are attached to a strong hub. This runner, Figs. 6 and 7, therefore,

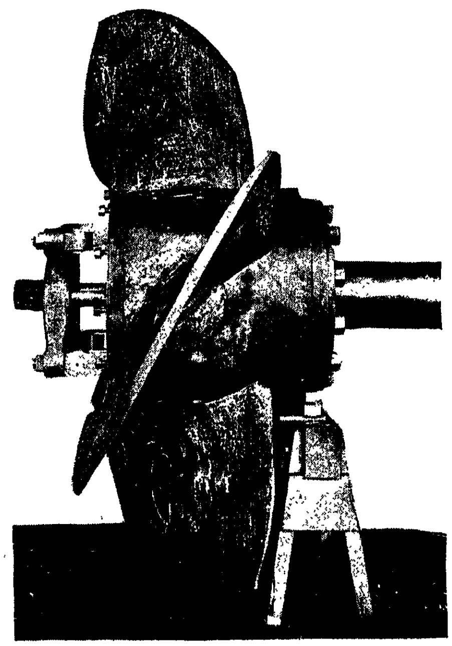

FIG. 7—AXIAL FLOW TURBINE WHEEL WITH ADJUSTABLE BLADES—OPEN POSITION

resembles a ship's propeller rather than a Francis turbine.

The Kaplan turbine shows three important new characteristics:

1. A vane-free transition space between the discharge area of the wicket gates and the runner entrance. The water leaving the gates in a whirling inward direction is deflected in an axial direction in this transition space and flows axially through the runner.

2. Wing shaped runner vanes, so spaced and proportioned that two adjacent vanes form a nozzle or double guidance for part of their radial extent and single guidance for the remainder.

3. Adjustable runner vanes.

Prof. Kaplan was the first to adjust the runner vanes and the wicket gates simultaneously. In the closed po-

sition, Fig. 6, the whole surface of the vanes, or buckets, lies approximately at right angles to the shaft axis. In this position the discharge is a minimum and the runner develops minimum power. With increasing wicket gate opening (increasing load) the vanes are opened so that the area of the water passage increases, Fig. 7. Each position of the runner vanes corresponds to a definite position of the wicket gates, and the correct relationship of these positions must be maintained if the efficiency at all rates of discharge is to be a maximum.

The simultaneous adjusting of the runner blades and wicket gates maintains the best conditions of flow throughout the entire range of output and results in the obtaining of exceptionally high part load efficiencies, thus securing very flat efficiency-load curves. Since the blade and gate angles and openings always

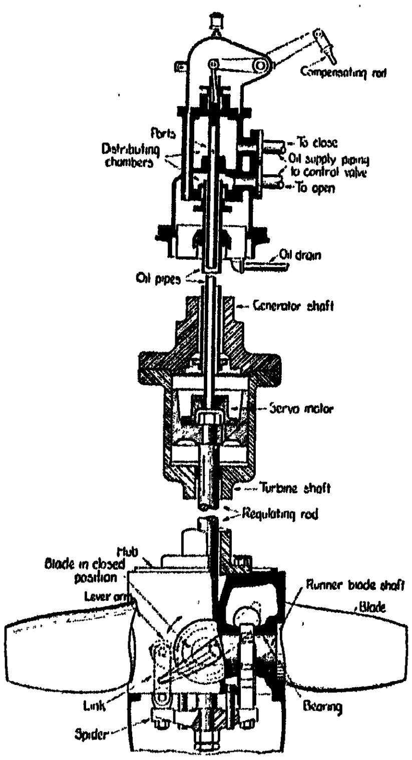

FIG. 8—HUB CASTING OF AXIAL FLOW TURBINE WHEEL

have the correct relationship to each other, the adjustable blade turbine operates with maximum smoothness and with minimum vibration and pitting.

The automatically adjustable blade turbine casing is constructed like the usual wicket gate casing except that the top plate contains an inverted curved cone-like projection which forms the inner surface of the transition space.

The construction of the runner hub which carries the movable blades requires special attention due to the relatively small space available. All of the operating connections for moving the vanes must be contained inside the single piece hub casting (see Fig. 8, lower view) and must be of such form that they will stand up indefinitely under the most severe service requirements without any adjustments. By very carefully utilizing every cubic inch of space, a design has been developed which has proved entirely satisfactory and reliable. The stresses must be held within very conservative limits to guarantee freedom from excessive strains and deformation and to reduce the possibility of wear to the absolute minimum. The moving parts of a Smith-Kaplan automatically adjustable blade runner, consisting of the regulating rod, the sliding cross and the link connection to the crank on the runner vane trunion, are clearly shown.

The bearings for the runner blade stems and the links are bushed with bronze to resist wear, and special provision is made to secure the blades against lateral displacement due to the large centrifugal forces developed.

In order to provide constant lubrication for the moving parts, the hub is filled with a heavy body oil. Each runner-vane trunion is packed against leakage where it goes through the hub body, so that oil loss is eliminated.

It is standard practise to make the runner vanes and hub of cast steel. Great care should be used to finish the vanes to templets, so that they will have the correct form and degree of smoothness required to offer the least disturbance to the flow of water through the turbine.

The movements of the gate control system and the runner-vane control system must be synchronized at all times, so that for every gate position there is a definite runner-vane position. This can only be accomplished when the gates and runner each have their own servo-motor and distributing valve. The regulating rod in the hollow turbine shaft is moved axially by a servo-motor (Fig. 8, center view) which is arranged between the flanges of the turbine and generator shafts and is rigidly connected to them, so that it revolves with the shaft. The servo-motor piston is directly connected to the upper end of the regulating rod which communicates the piston movements to the runner vanes. The servo-motor is operated by oil supplied under pressure from above (Fig. 8, upper view), through two pipes arranged concentrically within the hollow generator shaft.

The inner pipe carries oil to the lower side of the piston and is rigidly connected to it, moving upward and downward with the piston. The governor compensating mechanism is connected to the upper end of this pipe. The two pipes to the servo-motor terminate in two distributing chambers arranged one on top of the other, and mounted on top of the generator. These chambers receive the oil from the governor and collectively form the oil supply head.

Fig. 9 shows schematically the regulating mechanism. The governor itself is the usual speed governor which operates the wicket gates either through a vertical gate shaft or through servo-motors. In addition, this governor has a second distributing valve controlling

the flow of oil to the runner-vane servo-motor in the turbine shaft. A cam is connected to the gate operating mechanism and to the runner-vane compensating connection in such a way that the gates and runner vanes always move in the definite relationship required to give the maximum efficiency for every variation in load.

The correct shape of the cam on a given turbine varies with the head, the speed of the turbine remaining

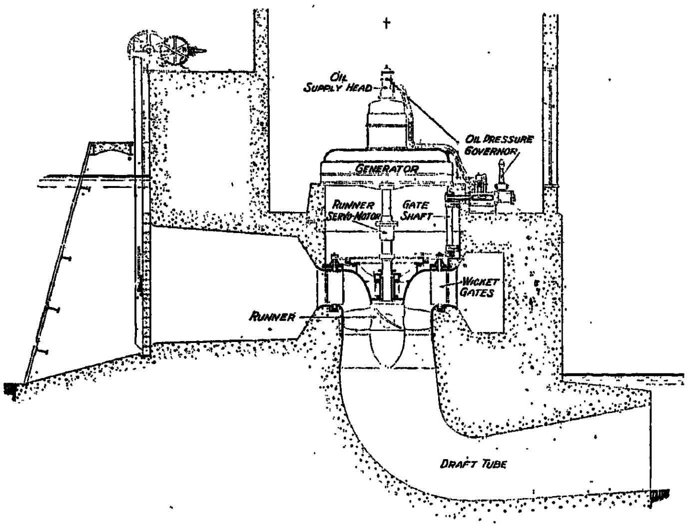

FIG. 9—SCHEMATIC VIEW OF REGULATING MECHANISM

constant. With a moderate range in head one cam will maintain such gate and bucket relationship as to produce the best efficiency, or very close to it, throughout the entire range of horsepower. When the variation in head is large, a series of cams may be used or a continuous warped surface cam can be designed and operated so that its position is moved as the head changes.

There are two types of generators suitable for use with this type of turbine; the more general two-bearing design, in which the thrust bearing and one guide bearing are located above the rotor with the second guide bearing below the rotor; and the umbrella design, in which the single combination thrust and guide bearing is located below the rotor. In the matter of cost and efficiency, there is practically no difference between the two designs, but the umbrella design has a number of advantages. It requires less head room under a crane and is easier to dismantle. Its single bearing runs in a bath of oil so that all oil piping is eliminated. It lends itself readily to almost any scheme of ventilation. The air may be taken directly from above or below the rotor, or the machine may be totally enclosed and a recirculatory scheme used with the coolers arranged conveniently around the periphery of the stator. If a scheme of excitation other than by means of a direct-connected exciter is used, the upper bracket may be omitted entirely. This may prove an advantage where it is desired to eliminate the building super-structure, and consideration should, perhaps, be given to motor-driven exciters. Where a dependable auxiliary source of power is available from which such exciters may be supplied, the problem is simple, but in most hydro-stations an auxiliary source is either not present or too small to handle all the excitation required. The motor-generator exciters may be supplied from the main units through suitable transformers, and in this case it might be advisable to provide them with a flywheel to maintain their output during faults. Some arrangement would also be necessary for starting up the dead station.

The field of application of the umbrella generator is for the large low-head units, and because of its inherent advantages it is used wherever possible. Fig. 10 shows a section through a typical modern umbrella generator.

It has been shown that the initial cost of a hydroelectric installation can be reduced by the use of high specific speed units, but this reduction is obtained at the expense of reduced part load efficiency, unless automatically adjustable blade turbines are installed. The installation of this type of turbine in turn increases the cost, thus tending to minimize the investment advantage due to higher speed. It is apparent, however, that with the higher part load efficiency to be obtained by the use of the automatically adjustable blade turbine, increased earning power is to be expected.

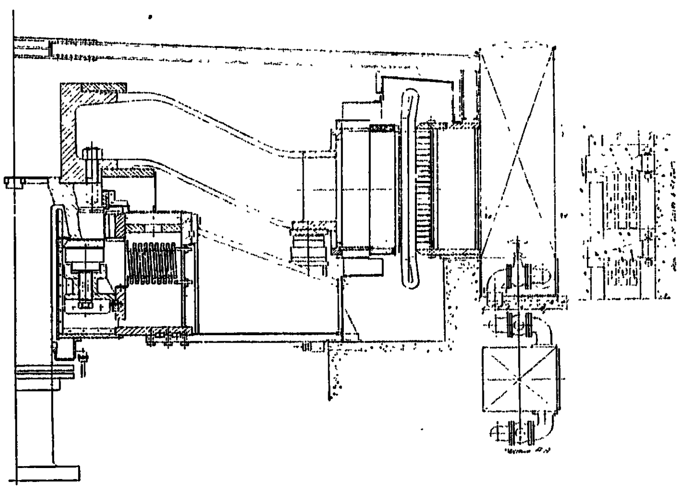

FIG. 10—SECTION THROUGH TYPICAL UMBRELLA TYPE GENERATOR

In order to study the effect of the characteristics of the various types of hydroelectric units on the yearly output, a kilowatt-hour output study has been prepared. A duration curve has been selected, which shows the cu. ft. sec. available during the year, and the head corresponding to the flow. It is to be expected that in the normal plant the head will decrease as the quantity of water increases. The duration curves are such as might be expected on a river having a fairly variable flow. A three-unit development has been chosen for purposes of illustra-

tion. A comparison has been made between three medium speed Francis units, three fixed blade axial flow units and three automatically adjustable blade axial flow units. The rated capacity of each unit is 28,500 kw. at extreme full load under 53-ft. head. The adjustable blade turbine has a surplus of 15 per cent above the maximum capacity of both the Francis and fixed blade turbines. Referring to Fig. 2, it will be seen that the size of the adjustable blade turbine can be selected to have this surplus capacity and still have the part load efficiency very much better than that of the other types. Even with their surplus capacity, the physical dimensions of the adjustable blade turbine are smaller than for the fixed blade turbines. Generally speaking, therefore, it is possible to operate an adjustable unit at a somewhat higher

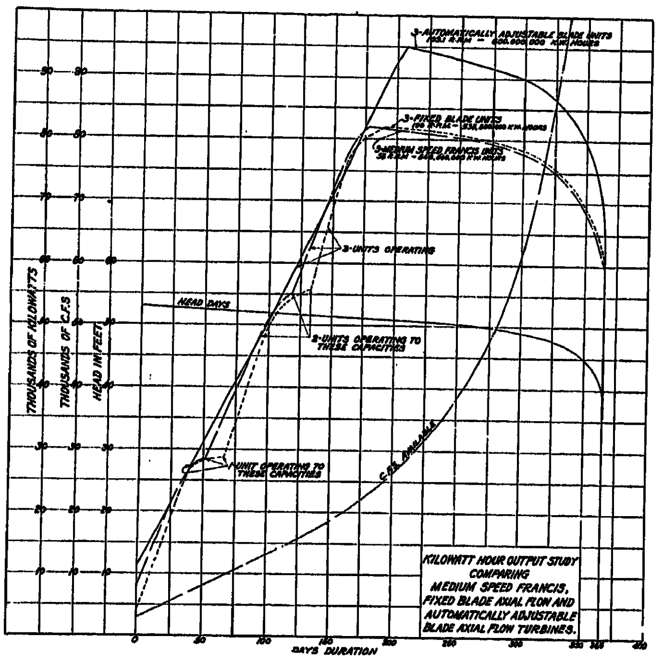

FIG. 11—OUTPUT CURVES OF THREE-UNIT STATION EQUIPPED WITH DIFFERENT TYPES OF WATER-WHEELS

speed than a fixed blade unit. Referring to Fig. 11, it will be noted that for the turbines used for the study, the adjustable unit is operated at 109.1 rev. per min., the fixed blade unit at 100 rev. per min. and the medium speed Francis unit at 58 rev. per min. The generator cost for the automatically adjustable units will, therefore, be somewhat less than for the fixed blade units.

The kilowatt output has been worked up from the head and cu-ft-sec. available, starting with one unit running and changing to two units as soon as additional kilowatts can be obtained by so operating. The operation is then continued with two units until increased output can be obtained by the use of three units. In making these curves it has been assumed that each unit, if desirable from the standpoint of economy in the use of water, can be operated to maximum load and that there is no necessity for maintaining a surplus for speed regulation.

It will be seen that in periods of low flow the automatically adjustable blade unit shows increased power output over the other types. As flood conditions are approached the greater capacity from the adjustable blade units is particularly marked. This increase is largely due to the fact that the size of these units was selected to secure a curve similar to that shown by Fig. 2.

It is of particular interest to note that the adjustable units produce 11 per cent more kilowatt hours than the fixed blade units and that the Francis and the fixed units have about the same yearly output.

If it is necessary to maintain a certain operating reserve, the adjustable blade units will prove to be even more advantageous than shown, because it will be necessary to operate the Francis and fixed blade units at even lower loads and, therefore, at lower efficiencies, for part of the low flow period.

The head and cu-ft-sec. duration curves are different for each development and, therefore, it is necessary to make a special study for each case. The illustration here offered shows a material advantage for hydroelectric units with automatically adjustable blade axial flow turbines, and it is believed that for most plants having a head of 70 ft. or under a comparison will show a similar increase in output.

Discussion

R. E. B. Sharpe: The advantages of the Kaplan type of turbine may be divided into two distinct headings:

First, in the higher part load efficiencies secured, and second, in the increased power possible under low heads and high-flow conditions often obtaining with consequent increased minimum capacity.

Referring to Fig. 4, the authors are somewhat conservative in the approximate maximum horsepower value as limited by physical dimensions. For the Francis installations for heads between 30 and 50 ft., it is believed that no difficulties would be encountered in constructing turbines of larger dimensions and greater power than indicated. For a head of 50 ft., for instance, a limiting power of 32,000 hp. at a speed of 67 rev. per min. is shown. The dimensions of the runner for this turbine correspond very closely with those of turbines actually being constructed both in this country and Canada. It is believed that for those conditions the maximum unit capacity may safely be increased to as much as 40,000 to 42,000 hp.

For the axial flow turbines, including both the fixed blade propeller runners and the movable blade Kaplan runners, it is believed that even a greater increase in maximum values is allowable. The maximum runner diameters which the authors have allowed for are apparently in the neighborhood of 290 in. The writer understands that Kaplan turbines are now being constructed for the Soviet government which will have a runner diameter of 30 ft. or 360 in. This information is rather meager, however, and perhaps the authors have more definite information as to this installation.

In classifying three factors as being Kaplan contributions, the authors, I think, ignore significant American contributions in this field. In the first two factors set forth, the work of Messrs. Moody and Nagler should be recognized. Particularly in connection with the second factor should the early work of Moody be mentioned. The Moody idea is the "double guid-

ance" feature with very liberal blade area as was exemplified in the Manitoba installation. This installation is recognized both in Europe and in this country as being the first actual proof that the propeller type of turbine can successfully be applied to heads as high as 56 ft.

The third factor, namely the adjustable runner vanes, is a Kaplan contribution.

Notwithstanding the Kaplan advantages, I cannot agree that, "for every installation the increased earnings will more han amply compensate for the greater investment involved." For instance, consider the St. Lawrence River developments involving a large amount of power with necessarily a large amount of units and with more or less steady flow and correspondingly small variation in head. Under such circumstances the advantage of the Kaplan type of turbine as compared to the fixed vane propeller type is not apparent. The steady flow and head conditions tend to wipe out the advantages of the Kaplan turbine and the lower costs and greater simplicity of the fixed vane type of propeller installation would, in all probability, result in the installation of that type of unit. The fixed vane type of turbine has also some advantage over the Kaplan type of turbine, in the matter of runaway speed, as a higher runaway speed is possible with the Kaplan type than with the fixed vane propeller type, with consequently a differential in generator costs.

G. A. Jessop and C. A. Powel: Mr. R. E. B. Sharpe's interesting discussion brings out several valuable points. In making up Fig. 4, the authors, as stated in the paper, intended to indicate the approximate limits of capacity. It is true that it is possible to exceed the limits as set. It is believed, however, that when going beyond the chart limits, hydroelectric engineers should consult the generator and turbine manufacturers before making definite plans or estimates. This will eliminate the danger of getting into a field of special design and development, thus increasing the costs beyond what might normally be expected.

It can also be stated that for the high-speed axial flow type of turbine, the specific speed as given by the chart may sometimes be somewhat increased. This would apply to plants where efficiency is not of paramount importance, but where first cost is the determining factor. In general, if the specific speeds as given are exceeded, it will be necessary to set the turbine somewhat lower than usual with respect to tailwater. It is recommended, however, that if it is considered desirable to use excessive specific speeds, the manufacturer be consulted and the entire setting be studied very carefully.

Referring to the economics of a Kaplan adjustable runner installation, as pointed out, it is necessary to make a study for each set of conditions. The cost of the entire development will be increased only a very few per cent by the use of automatically adjustable blade runners rather than fixed blade runners. It follows that a few per cent increase in kilowatt hour output will pay for the increased cost. There are only a very few developments where the head and flow are found to be so steady that adjustable blade runners are not of material advantage. For the small installation, in addition to a practically fixed head and flow, it will be necessary to have a fixed load to wipe out the advantages of the adjustable runner. For the very large installation having a large number of units, a variable load might be taken at good efficiency by starting and shutting down units as the load comes on or off. This method of operation has many disadvantages which can, to a large extent, be eliminated with the Kaplan turbine.

Trend in Design and Capacity of Large Hydroelectric Generators

BY M. C. OLSON*

Associate, A. I. E. E.

Synopsis.—This paper describes the recent trend in design of large water-wheel driven generators. New features of mechanical construction made possible by fabricated designs are particularly emphasized, and illustrations of some recent machines are given. The 77,500-kv-a. generators for the Dnieprostroy project in Russia, which will be the world's largest hydroelectric generators, are described. In conclusion, some of the future possibilities, such as outdoor machines and multi-speed designs, are discussed.

WITHIN the last few years many changes have been introduced in the mechanical and electrical design of large hydroelectric generators. The purpose of this paper is to present a few of the salient features of some recent installations, and to indicate the trend of progress in design of this class of machines, as indicated by the experience of one manufacturer.

As interconnected systems are continually growing in size and the load carried by an individual generating unit becomes a smaller and smaller proportion of the total load, it is increasingly feasible and desirable to operate some units of a station or some stations of a system at the most efficient load. With this condition of operation with higher load factor, there is an ever increasing demand for larger units and higher efficiencies.

Fig. 1 shows the trend in maximum capacity of large, vertical water-wheel-driven generators, built by one company, during a period of 30 years. The largest units shown on this curve are the 77,500-kv-a. generators, which are now being built for the Dnieprostroy Hydroelectric Development of Russia. These machines will be the world's largest hydroelectric units, both as to rating and physical size.

The trend in maximum capacity of large horizontal water-wheel-driven generators, built by this company, during the same period as mentioned above is shown in Fig. 2. The largest unit shown on this curve is the 55,000-kv-a., 360-rev. per min., generator, now being built for the Sao Paulo Tramway Light and Power Co., Brazil. This generator will be driven by double overhung impulse water-wheels.

During the past six years, on machines above 5,000-kv-a., the horizontal water-wheel-driven generators, in kv-a., were 14 per cent of the total water-wheel-driven generators. In 1924, the horizontal water-wheel driven generators[8] were almost in the same ratio or 13.5 per cent. This indicates a fairly stable ratio.

One can appreciate the growth of water power[1] in the United States, from Fig. 3 which shows a curve of total water power developed in horsepower starting from the year 1870, up to 1930. Approximately 36 per cent of the total power generated by public utility power plants in 1929, was produced from water power.

According to the U. S. Geological Survey, water power has generated more than one-third of the total

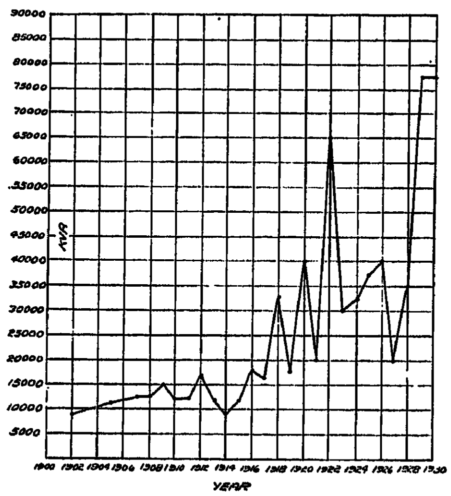

FIG. 1—TREND IN CAPACITY OF LARGE VERTICAL HYDROELECTRIC UNITS

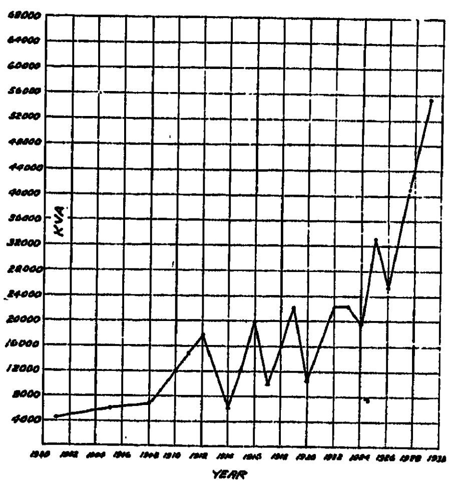

FIG. 2—TREND IN CAPACITY OF LARGE HORIZONTAL HYDROELECTRIC UNITS

electricity produced every year since 1919. In the year 1928, 40.6 per cent of the total power generated was produced by water power. The total water power in the United States available 50 per cent of the time

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8. For references see Bibliography.

is 59,000,000 hp., so that at the present time, only 23 per cent is developed. If it were feasible to develop all the water power sources of the United States, the total capacity of water-wheels that would be installed is placed at 85,000,000 hp.

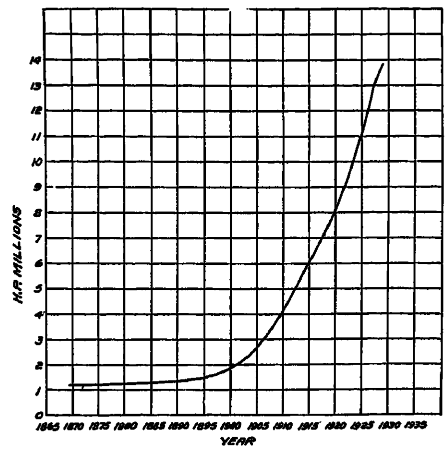

FIG. 3—GROWTH OF WATER POWER DEVELOPMENT IN THE UNITED STATES

FABRICATED CONSTRUCTION

Radical changes have been made in the design, construction and appearance of water-wheel-driven generators during the last few years due to the use of rolled steel plates and fabricated structures in place of castings. As a result of the introduction of welded steel plate construction, generators have been made more reliable mechanically, lighter in weight, and much more adaptable for special ventilating or constructional requirements. Also, shorter deliveries have been made possible. With a range of speeds from 60 to 720 rev. per min., hydroelectric generators must have widely varying designs, which can be more easily made with fabricated than with the older cast construction.

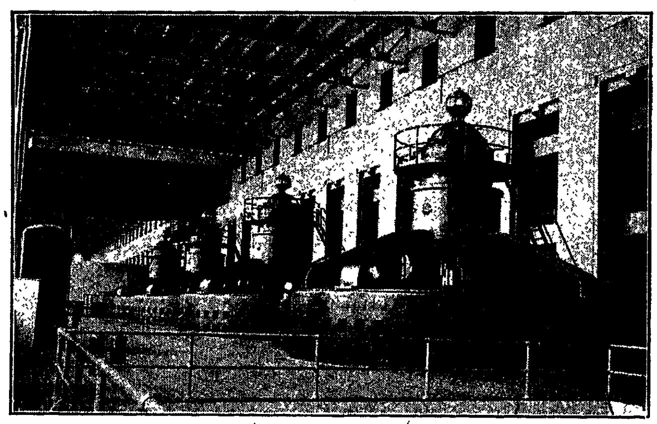

FIG. 4—CONVENTIONAL DESIGN WHEN CASTINGS WERE USED
32,500-kv-a., 100-rev. per min., 12,000-volt generators

The Muscle Shoals generators Fig. 4 are typical of the latest period of cast frame design. On the Conowingo 40,000-kv-a. generators,[2] the mechanical parts except the upper bearing brackets, which consisted of a cast central hub and arms were fabricated.

One of the first large generators with completely fabricated construction was the 33,000-kv-a., 125-rev. per min., 6,600-volt generator, for the Brazilian Hydro-Electric Company. This machine illustrated in Fig. 5 has practically no castings.

The upper bearing bracket consists of a fabricated central hub to which are bolted radial steel arms. The hub consists of top and bottom plates between which are welded radial steel ribs. The fabricated arms are attached to the central hub by means of reamed bolts and also by plates at the top and bottom of each arm. A steel ventilating hood completely surrounds the frame.

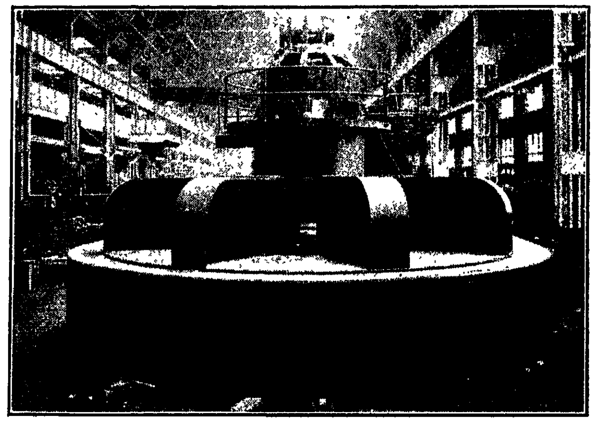

FIG. 5—33,000-KV-A. 125-REV. PER MIN. 6,600-VOLT-50-CYCLE GENERATOR WITH PRACTICALLY NO CASTINGS

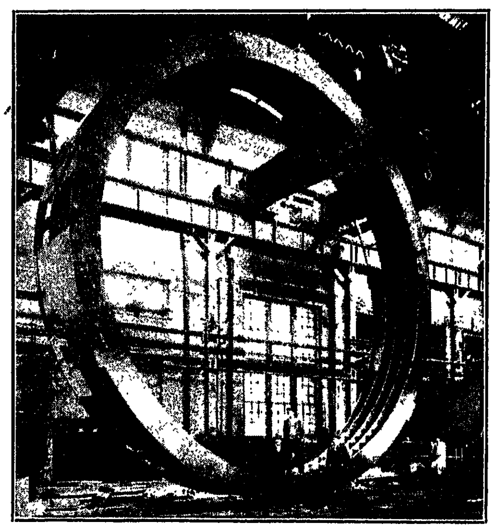

FIG. 6—STATOR FRAME FOR 47,000-KV-A., 81.8-REV. PER MIN., 13,800-VOLT VERTICAL GENERATOR FOR SPIERS FALLS, N. Y.

FEATURES OF STATOR DESIGN

Welding and the use of rolled steel plate have progressed to such an extent that it is now possible to make almost any size of frame and by designing it in sufficient sections to ship it to the installation without exceeding permissible weights or clearances.

Fig. 6 shows the stator frame for the 47,000-kv-a.,

vertical water-wheel-driven generator for Spiers Falls. This frame has an outside diameter of approximately 37 ft. and a height of 7 ft., is made in six sections and weighs 100,000 lb. The numerous supports between the ribs make a very rigid construction. Being made of steel, it is much lighter and stronger than a cast frame. The ventilating openings in a design of this kind can be conveniently placed at any desired location. The punchings and windings will be assembled in this frame at destination.

The novel frame design of the 26,667-kv-a. generators, for the Central Maine Power Company, shown in Fig. 7 illustrates the flexibility of design characteristic of fabricated construction. The frame is of conventional circular shape when viewed from the outside, but the air gap circle is eccentric with the outside, thus giving a volute form of ventilating air space behind the laminations. The design permits the collection of air from the stator ducts around the entire periphery, and its com-

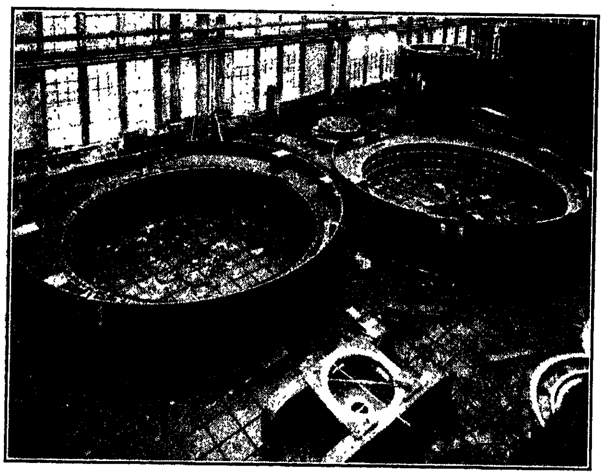

FIG. 7—ECCENTRIC STATOR FRAMES

For 26,667-kv-a. $138\frac{1}{3}$-rev. per min. 13,800-volt vertical generators

plete discharge from one side of the frame, thus simplifying station duct work and construction. The design has obvious advantages over the use of a standard concentric frame with external eccentric ventilating hood.

FEATURES OF ROTOR DESIGN

Fig. 8 shows the rotor spider and Fig. 9 the assembled rotor of the 33,000-kv-a. generator. The center spider is a fabricated structure consisting of I beams bolted between circular plates. The rim is made of segmental punched laminations mounted on the center spider. The segments are punched for pole-piece dovetail, rim key and for through bolts for clamping the core. At the end of the rotor spider arms are welded vertical ribs, slotted for receiving the rim keys.

In this design, the rim is not anchored to the rotor spider, but the torque is transmitted through axial keys, which fit into notches in the rim punchings and slots on the spider arm ribs. This leaves the rim free to expand under centrifugal stresses without transferring any stress to the spider, and thus makes the design of the rim and the spider independent and their stresses definite. When rim and arms are rigidly fastened together, the radial arm tension and the peripheral rim tension divide the total stresses in inverse ratio to their

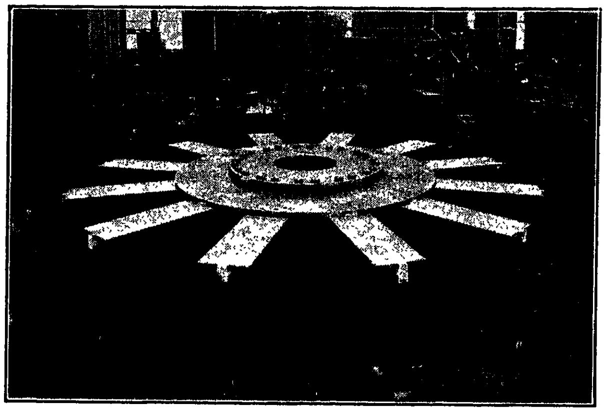

FIG. 8—ROTOR SPIDER

For 33,000-kv-a. vertical generator

elastic deformations. The uncertainties thus introduced are avoided in this new design. A similar free rim construction was also used in the Conowingo generators.[3]

Numerous square holes are punched around the periphery of the rim for the insertion of coil springs which support the field coils and keep them tight against any possibility of shrinkage of insulation.

Fig. 10 shows a 10,000-kv-a., 180-rev. per min., 13,800-volt vertical water-wheel-driven generator rotor with poles completely assembled. A new type of braking surface consisting of machined segmental

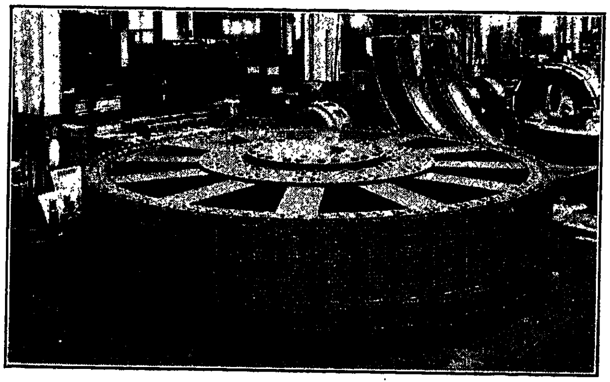

FIG. 9—FABRICATED ROTOR WITH LAMINATED RIM

For 33,000-kv-a. vertical generator

plates attached to the rotor-spider arms by means of tapped bolts is clearly shown. The air or oil operated brakes act against this surface to stop the rotor in case of gate leakage.

A sectional view of this generator is shown in Fig. 11. It has a direct-connected exciter, two guide bearings and

a thrust bearing and is constructed with welded steel plates and structural steel parts throughout.

The largest fabricated rotor spider up to the present time is shown in Fig. 12. This rotor spider is in an inverted position in the process of machining the segmental braking plates. The outside diameter of these plates is nearly 29 ft. It is only exceeded in size by the rotors of the 77,500-kv-a. generators that are being built for the Dnieper River Project.

On account of the thrust bearing being located beneath the rotor spider, the arms are designed with a downward curve so as to make the center line of the laminated rim considerably below the center line of the hub. The web plates of these arms are flame cut to the desired shape. The top and bottom plates are formed to this shape and welded to the web plate. Ribs or stiffening plates are welded to each side of the web plate to give additional rigidity. The eleven arms of

FIG. 10—ASSEMBLED ROTOR SHOWING SEGMENTAL BRAKING PLATES

For 10,000-kv-a. 180-rev. per min. 13,800-volt vertical hydroelectric generator

the rotor are bolted to thick steel plates at the top and bottom of the arms by means of body bound bolts. The plates are attached to the steel spider hub by body bound stud bolts.

In order to lessen the windage on this large rotor, the top and bottom of the arms will be partially covered by a sheet steel covering. The maximum overspeed of the water-wheel on this unit is 192 per cent or 157 rev. per min.

VENTILATION

Enclosed System. So many advantages are obtained by the use of the enclosed system of ventilation that there is an increasing tendency to adopt this method.

This system allows only clean, cool air to be circulated through the machine, thus insuring a clean machine and eliminating shut down for cleaning—therefore, reducing the maintenance cost. This arrangement requires the minimum amount of duct work, lessens fire hazards, and makes a more quiet machine, thus improving operation room conditions.

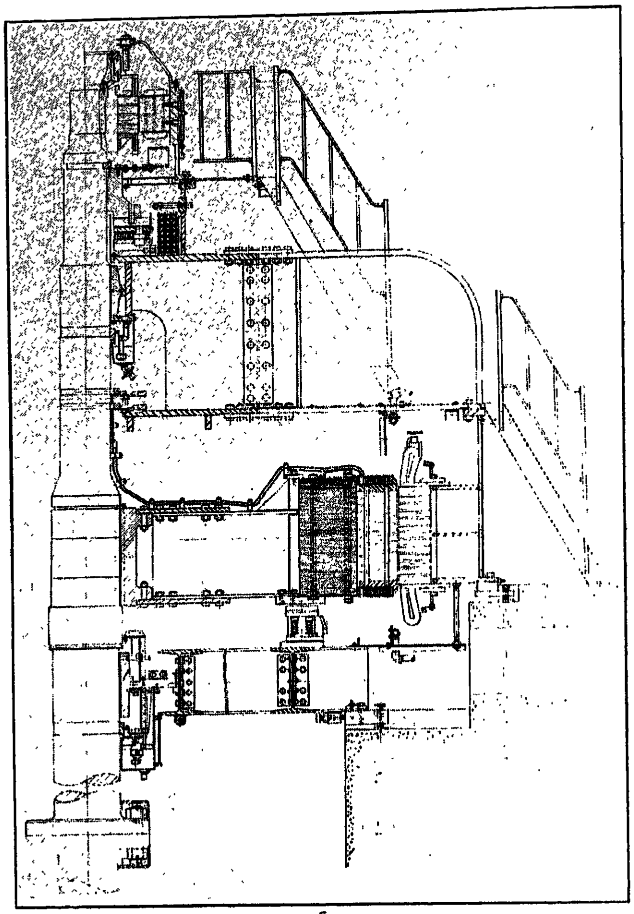

FIG. 11—SECTIONAL VIEW OF THE 10,000-KV-A., 180-REV. PER MIN., 13,800-VOLT VERTICAL GENERATOR

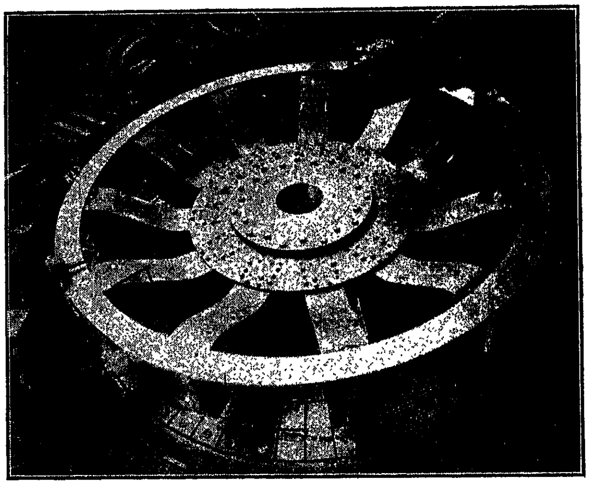

FIG. 12—ROTOR SPIDER IN AN INVERTED POSITION IN THE PROCESS OF MACHINING THE SEGMENTAL BRAKING PLATES

For the 47,000-kv-a. generator

The 47,000-kv-a. generator, shown in Fig. 13, has 12 surface air coolers located in the ventilating hood outside the stator frame. Two temperature detectors

90 deg. apart are located in the incoming air to the rotor so that its temperature can be read at the switchboard.

Fig. 14, shows the Lake Chelan plant of the Washington Water Power Company, arranged with enclosed

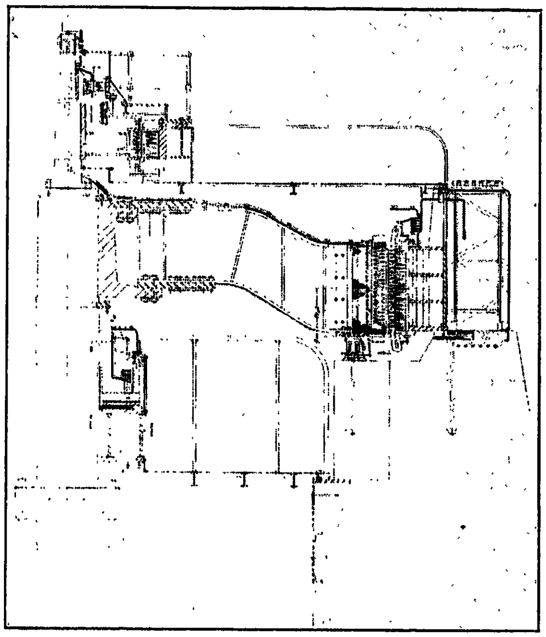

FIG. 13—CONSTRUCTION OF 47,000-KV-A., 13,800-VOLT, 60-CYCLE, 81.8-REV. PER MIN., OVERHUNG TYPE VERTICAL WATER-WHEEL DRIVEN GENERATOR

system of ventilation. In this station, there are two 30,000-kv-a., 300-rev. per min., 11,000-volt generators. The eight coolers for cooling the recirculating air are located in the ventilating hood and are arranged vertically so that they may be easily installed and cleaned.

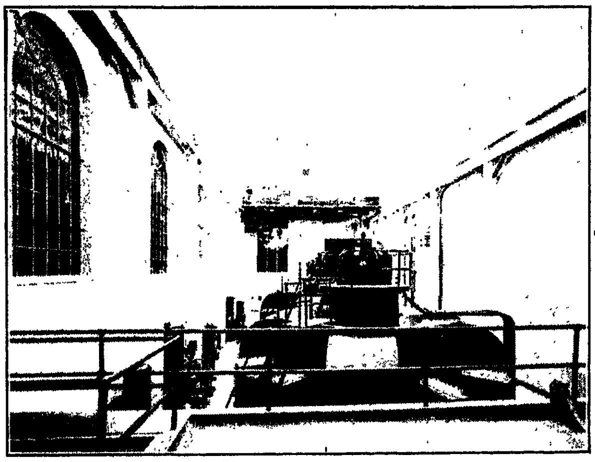

FIG. 14—LAKE CHELAN PLANT OF THE WASHINGTON WATER POWER CO. SHOWING ENCLOSED SYSTEM OF VENTILATION

The air comes out at eight places in the stator frame and passes circumferentially through the coolers to the pit underneath the machine and also to the space above the rotor between the bearing bracket arms.

Temperature Rise Before and After Cleaning. If machines are not kept clean, and air ducts are partly or wholly closed and other openings restricted, there certainly will be considerably higher temperatures when this condition obtains.

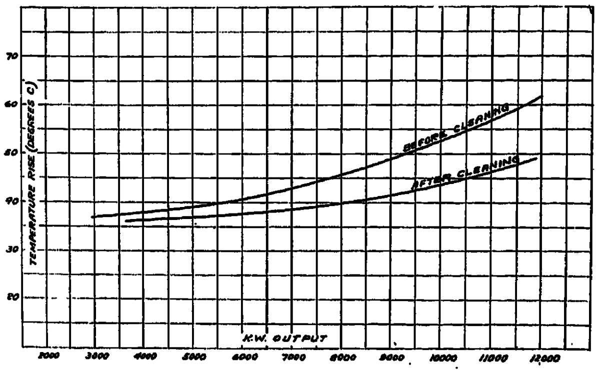

FIG. 15—CURVE SHOWING TEMPERATURE RISE BEFORE AND AFTER CLEANING

As a matter of interest, Fig. 15, shows curves of temperature rise before and after cleaning on an 11,000-kw., 0.9 power-factor, (12,222-kv-a.), 514-rev. per min., 6600-volt vertical water-wheel-driven generator. At full load the temperature rise is 11 deg. cent. lower after cleaning the machine.

OVERSPEED REQUIREMENTS

Rotors of water-wheel-driven generators are designed to withstand the maximum runaway speed of the water-wheels which is usually from 80 to 100 per cent over normal speed.

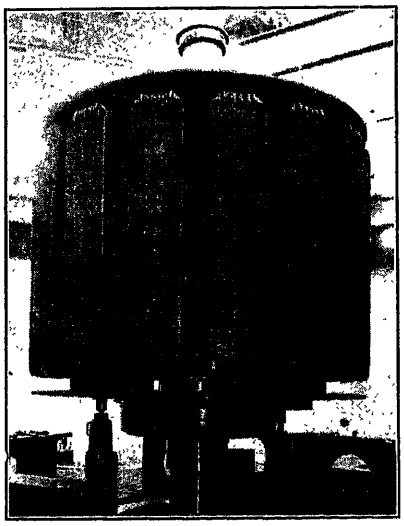

FIG. 16—ROTOR OF 35,000-KV-A., 375/450-REV. PER MIN. GENERATOR IN HIGH-SPEED TESTING PIT

Occasionally, it is required that rotors be tested at the overspeed before leaving the factory, but with improved forms of fabricated and welded construction this requirement is being less and less encountered.

Fig. 16, shows the rotor of the 35,000-kv-a., 375/450-

rev. per min. generator, in the high-speed testing pit. It was run at 85 per cent above the 450-rev. per min., 60-cycle speed, or 833 rev. per min. for one minute. The peripheral speed of the rotor at the air gap at this overspeed is 28,500 ft. per minute.

OVERHUNG VERTICAL GENERATORS

In recent years, there has been an increasing tendency toward the adoption of the overhung type vertical generator. The outstanding advantage of this type is the reduction of over-all height, which allows a corresponding reduction in height of crane. The chief disadvantage is the free length of shaft above the bearing, and the consequent possibility of vibration at high speeds. The design is, therefore, well suited to low-speed generators, but is not applicable to machines in the highest speed range.

Some of the first machines of this kind manufactured by the company with which the author is associated, were built seven years ago. They are rated 8,200 kv-a., 150 rev. per min., 6,600 volts.

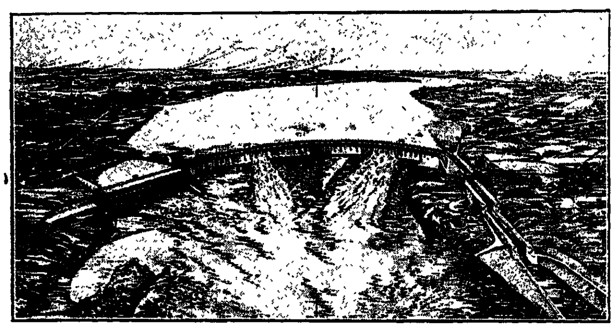

FIG. 17—PERSPECTIVE OF THE DNIEPER RIVER PROJECT AT KICHKAS REPUBLIC OF UKRAINE, RUSSIA

Since that time, a large number of machines of this type has been built. The largest in physical dimensions, which is now being built for the New York Power and Light Co., Spiers Falls, N. Y., is rated 47,000 kv-a., 81.8 rev. per min., 13,800 volts. This generator will be driven by a Francis type water-wheel rated 57,000 hp. It will require 6,200 sec-ft. to operate it at full load, or the entire flow of the Hudson River, during low-water period. The net head is 81 ft.

A sectional view of this unit is shown in Fig. 13, which forms an interesting contrast with Fig. 11.

The thrust bearing for this machine is located just below the rotor spider. It is the largest combined guide and thrust bearing ever manufactured, is 84 in. outside diameter, and will carry a total weight of 1,365,000 lb., of which 815,000 lb. is the combined weight of water-wheel runner and shaft and hydraulic thrust. The guide bearing is 52 in. diameter by 26 in. in length. The stationary ring, rotating ring, and guide bearing are all split to facilitate inspection.

Thermometers with bell alarm contacts are provided for the thrust and guide bearings, and an oil level gage with an alarm contact, to indicate the height of oil in the bearing, is also furnished.

The bracket for supporting the thrust bearing consists of two main girders 26 ft. long and 7 ft. high These girders are made up of welded, steel plates. Between these girders is bolted the fabricated thrust-bearing housing.

DNIEPER RIVER GENERATORS

There are now being constructed the world's largest water-wheel-driven generators for the Dnieper River Project. These are rated 77,500 kv-a., 88.25 rev. per min., 13,800 volts, 50 cycles. Five of these machines are now being built and when completed this plant will have nine generators, each driven by 84,000-hp. water-wheels—the largest hydraulic turbines ever built. The average operating head is 116.5 ft. The ultimate installation will be 750,000 hp. and it is expected that the plant will be completed by 1934.

Fig. 17 shows a perspective of this immense installation at Kichkas, Republic of Ukraine, which has been furnished through the courtesy of Colonel H. L. Cooper, the consulting engineer on this project. The construction of locks and the raising of the water level of the Dnieper River will make it navigable for 1,500 miles.

An idea of the proportions of these generators is given by the following comparison of their principal weights and dimensions with those of the largest American and European[4] machines heretofore built.

	Dnepro-stroy	Niagara	Spiers Falls	Ryburg-Schwor-stadt
Date completed	1931	1923	1930	1929
Kv-a. rating	77,500	65,000	47,000	35,000
Speed in rev. per min.	88.2	107	81.8	75
Frequency in cycles	50	25	60	50
Voltage	13,800	12,000	13,800	10,500
Power factor	0.8	0.8	0.8	0.7
Outside diameter—ft.	41	31	37	44
Over-all height from bottom of stator frame to top of machine—ft.	26	27	16	..
Height from face of coupling to top of machine—ft	41	27	24	32
Weight of rotor—lb.	978,000	785,000	540,000	..
Total weight—lb.	1,740,000	1,517,000	976,000	1,210,000

These Dnieprostroy machines will be of the conventional type with thrust bearings located in the upper bearing brackets. There are two guide bearings, one beneath the thrust bearing and one in the lower bearing bracket.

An auxiliary generator rated 750 kv-a., 68 poles, 2300 volts, is mounted above the thrust bearing on the main generator shaft and a direct-connected exciter for the auxiliary generator is mounted above it. As on machines of smaller sizes, these units are also made of fabricated and welded parts.

The design of the upper thrust deck is similar to that shown in Fig. 5, having 12 arms, and weighing 250,000 lb. The lower bearing bracket is made of structural steel girders 36 in. high.

The rotor has twelve fabricated steel arms, each bolted between two heavy steel plates by means of tapered bolts. The steel hub for the rotor spider weighs 62,700 lb., is nearly 8 ft. in diameter over the flanges, and is over 6 ft. high.

Largest Thrust Bearings. The General Electric thrust bearings used on these machines are the largest ever designed, having an outside diameter of 92 in. and an inside diameter of 31 in. The total weight carried on a bearing is 1,900,000 lb., including the weight of water-wheel, water-wheel shaft, and hydraulic thrust.

Shaft. An idea of the size of this machine can be obtained from the dimensions of the shaft, which is 40 in. in diameter. The diameter over the coupling flange is 70 in., the total length of shaft is 36 ft., and its weight is 136,000 lb. To assure proper alinement of shafts on these large units, the water-wheel shaft is lined up on centers with the generator shaft. Coupling bolts are fitted and face of collar trued up.

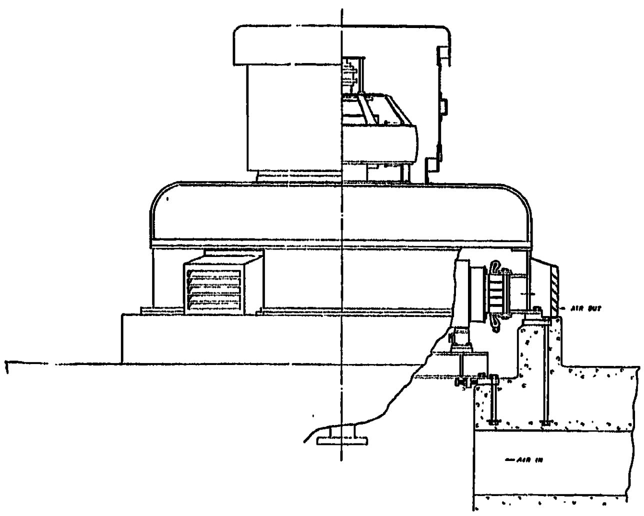

FIG. 18—PROPOSED CONSTRUCTION FOR AN OUTDOOR WATER-WHEEL DRIVEN GENERATOR

FUTURE POSSIBILITIES

It is interesting to speculate on the possibilities which the future holds in store.

In respect to capacity, it is clear that the limit has by no means been reached. There is no reason why generators of 150,000-kv-a. rating, at speeds of 150 rev. per min. or less, can not be built if they are needed, so that it is extremely probable that the present trend toward larger capacities will continue.

In respect to voltage, it is feasible to build generators of normal design for 24,000 volts and higher, though there is no present demand for voltages much in excess of 15,000 volts. At the transmission voltages used for large stations, the use of transformers is imperative at the present time, and so the choice of generator voltage is based on considerations of station equipment rather than transmission. In large stations it may be found economical to generate at 22,000 volts, but it seems more probable that lower voltages will continue to be used, while double windings[5] and unit operation of transformers and generators will be brought in to reduce the switching requirements and improve stability.

The generator speeds required with present hydroelectric practise, except in very high-head developments, seldom bring in any mechanical limitations, so that the speeds of future water-wheel generators will be limited by considerations of turbine design. The recent developments of the propeller and Kaplan turbines,[6] making it possible to use higher speed wheels in low-head plants, will create a trend toward higher speeds, and will make feasible the development of very low-head plants.

An interesting possibility of the future is the use of multi-speed generators to permit efficient use of the water under varying conditions. Propeller type turbines with adjustable pitch blade, can be set to give the greatest efficiency under the actual operating conditions. By designing the generator for pole changing, however, a similar effect can be obtained electrically. Two-to-one pole changing is well known, but it gives too great a speed change for normal conditions. Recently a three-to-two speed salient-pole synchronous motor has been built which gave satisfactory performance at both speeds, without great sacrifice of characteristics at either speed. The same design can be applied to a water-wheel-driven generator, making it possible to develop power at a fixed frequency and voltage with either full or two-thirds speed.

The overhung type of vertical water-wheel-driven generators will likely increase in popularity.

Fabricated construction will continue, without doubt, until all important water-wheel generators are so made. With increasing appreciation of the flexibility of design made possible by this development, it is probable that there will be a strong tendency to adapt the generator frame design to the power house. The final result of this trend may well be the adoption of outdoor generator designs, of which several are under consideration. Fig. 18, illustrates a proposed form of outdoor construction for a water-wheel generator.

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Automatic Operator for Economy Control
Applied to Hydroelectric Generator Stations

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Non-member

Synopsis.—This paper deals with the great importance of economic division of load between various units in a hydroelectric plant and the proper combination of units for any given output allowing for the proper reserve required. It points out that in the past, the attempt to achieve ideal economy of operation has been handicapped by the human element. The duties of the average operating force are usually such that the constant maintaining of accurate loading schedules for best economy is a physical impossibility when the usual manual operation is employed.

The solution for this problem has been found in the development of the "automatic operator" designed specially for each plant through the combination of the preparation of ideal schedules, of economy of operation adapted to the particular system requirements and the installation of special automatic control equipment which permits the rigid enforcement of these ideal schedules.

The actual application of the automatic operator and the results obtained in the Norwood Plant of the Carolina Power & Light Company and the Morony Development of the Montana Power Company are fully described.

* * * * *

THE improvements in hydraulic turbine and hydraulic plant design have gradually reached a point where further increases in maximum over-all efficiency can be of very small degree and will probably be effected only as a refinement in the design. Considerable study is now being directed toward broadening the range of high efficiency of hydraulic turbines by increasing the part-load efficiencies. New types of propeller turbines with automatically adjustable blades are one of the great steps forward and bring to low-head plants a relatively flat efficiency curve which has hitherto been found only in the medium and high-head installations.

One aspect of hydroelectric practise, however, has just recently been receiving greater attention. This particular feature has to deal with the economic operation of generating units in order to secure the full benefits of the high efficiency characteristics of the units themselves. It has been found from studies of a number of plants that the average operating efficiency rarely equals the maximum over-all efficiency of the station. In one of the recent large hydroelectric plants the over-all efficiency of the station was found from test to be approximately 90 per cent. Detailed analyses showed that the maximum as attained in daily service was only on the order of 80 per cent. The margin between these two figures was traced directly to inefficient loading of the plant and to inefficient load distribution between the various units in service.

Other factors, such as the unnecessary lowering of the maximum operating head and excessive draw-down on small ponds and storage reservoirs, greatly impair a high over-all efficiency of station operation. Attention directed to these factors indicates a very fruitful source of study with the result that improvements in operating practise can be effected and losses recovered in proportions that have hitherto been unsuspected.

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Hydroelectric power plant operation, particularly when interconnected with large power systems with a fair proportion of steam generating plants available, must be considered in combination with these other plants so that the system as a whole will reflect the benefits of economies which can be made in hydroelectric plant operation.

Considering only the hydroelectric plants in this paper, the operation of such stations must be considered with reference to the capacity of the station, the stream flow available, the market for power and the operating characteristics of the system to which this power is being supplied. Assuming that the plant has already been designed and installed, the general problems of operation in so far as they are considered with respect to economy, may be classified as follows:

1. Economic load distribution between units for any given station load and combination of generating units.
2. The economic output of the station corresponding to the points of maximum efficiency for the various combination of units.
3. The maintenance of the economic number of units or combination of units in service for any given load on the station.
4. The maintenance of maximum operating head and conservation of flow.
5. The control of pond levels with respect to flow when surplus water is available.

These five classifications deal principally with the hydraulic characteristics of the plant itself. Two other factors, dealing with the relation of this particular plant to system operation, are as follows:

6. The maintenance of sufficient system reserve capacity to provide for system requirements, to be operated in parallel with the system, and carried at a minimum cost. This may be divided into two types; reserve for immediate availability and reserve for delayed availability.
7. The maintenance of a fixed draft of water from storage reservoirs or through run-of-river plants, to provide for the proper water balance on a given stream

where more than one station is installed, in order to provide for plants lower down on the river or to absorb the discharge from plants above the one under consideration.

There are two other considerations which may be classed as those which affect the type of service rendered by the power company, namely:

8. Automatic frequency control to maintain constant frequency with the possible refinement of maintaining constant average frequency where electric timekeeping is a factor.

9. Automatic power-factor correction to improve line and distribution voltages and power factor within the limits of the machine capacities and by utilizing from time to time surplus machines as synchronous condensers.

Each of these items represents a field of study in itself and with the proper coordination of these elements, or as many as would be applicable or desirable in a given plant, the over-all operating efficiency of any given station can usually be improved and in addition, reflect an improvement in the over-all operation of the system.

Practically all of the considerations as outlined above have been given considerable study as individual problems and as such are fairly well known and fairly well appreciated by designing and operating engineers. A number of systems set very high standards of operation by preparing economic loading schedules and endeavoring to have the plants operated in accordance with these schedules. There has been a number of articles published in the technical press, the most comprehensive of which was that presented by Mr. Frank H. Rogers and Mr. Lewis F. Moody, at the Third Hydroelectric Conference held in 1925, on the subject of "Interrelation of Operation and Design of Hydraulic Turbines." This paper deals principally with the first problem, namely, the economic load distribution between units, but other elements are considered including the design factor of determining the proper combination of units to install in a given plant, based upon the normal river flow and the load factor under which the plant would operate.

System Analyses

A brief outline of the scope of an analysis of operating economy on any generating system will be of interest. The first step in any comprehensive study of system and plant economy should be an accurate field test of each type of unit in service in a particular plant and preferably, each unit even though they are of the same type. These tests establish the characteristics of the machines under actual service conditions and very often bring to light unsuspected losses resulting from many different causes. An entire paper could be written dealing with this subject alone. Greater utilization of field testing results in improved standards of operation and increased efficiency of utilization of the plant itself. Field tests today can be made very cheaply and simply by either the Allen method or Gibson method in practically all plants, and where these methods can not be applied, it is usually possible to employ current meters with more or less accuracy, depending upon the type of meter used and the methods employed in the flow measurement.

Assuming then, that the first step has been taken, namely, the accurate determination of the unit operating characteristics; schedules of economic load distribution between the units can be prepared, which determine the proper loading of the units and the proper combination of units for any given output on the generating station. With existing plants where operating records are available, it is usually possible with a brief analysis of the operating records taken from the daily log sheets, to determine the relative operating efficiency of the station.

In cases where the accurate test data are not available, it is possible that a combination of the manufacturer's test curves and the manufacturer's expected curves combined with power-gate opening tests on the actual installation will provide sufficient information to prepare operating charts for units having similar characteristics.

For units of dissimilar characteristics, which of course include units of different specific speeds and capacities, and occasionally, units having the same capacities and speeds, but built by different manufacturers, it is necessary to make field efficiency tests, since the information available by approximate methods is not sufficiently accurate to determine the relative loading of these dissimilar units.

The over-all performance of the station is the efficiency relation which is of most value for power plant operation. The combined efficiency of the turbine and generator is not sufficient for this work since it does not include penstock losses, intake losses and other similar factors which have a decided bearing on the station performance. Allowances should be made for excitation and for auxiliary power so that a complete operating efficiency is represented.

With the station and unit characteristics determined, an over-all schedule for operation can be prepared which, for each load on the station, will specify the number of units required to carry the load; the proper combination of units which should be in operation if they are of unlike characteristics; the proper loading for each unit in order to maintain the best over-all efficiency.

Based upon an estimated percentage of adherence to this schedule, the question of load factor, load demand and the rate of draw-down of the forebay can be studied, in their effect on the maintenance of the maximum head. In cases where appreciable pondage or storage is available, a nice balance can be worked out between the permissible rate of draw-down during the demand hours and the building up of the head water level at night.

With low and medium head plants, particularly those which form a series of development without having the head overlap between plants, it is of great importance to

maintain the maximum operating head and prevent the loss in output and efficiency. In large systems where the output of any single plant does not form a large proportion of the total capacity, the operation of the individual plants are subject to a fair amount of flexibility which will permit the run-of-river plants to operate at maximum efficiency and also to maintain maximum head. In low-head plants, particularly those with heads below 30 ft., a very slight change in level in the forebay or the tailrace results in an appreciable loss in power. Operation at an inefficient point increases the draft on the reservoir and also discharges a surplus of flow downstream which, in turn, increases the tailwater level and thus doubly decreases the head and still further aggravates the losses incurred. It may be seen, therefore, that the closest attention should be directed toward efficient operation in low-head plants, considering the three factors involved namely, the economic load distribution between units, the economic output of the station and the maintenance of the maximum operating head.

In such plants still another factor is involved in periods of excess flow namely, the controlling of the forebay level through the spillway gates so that the maximum head is obtained during the high water season particularly in the intermediate zones where the excess flow has not reached the proportions of a flood. In such times the operation of the plant should still give due consideration to efficiency and should draw as much flow as possible through the units on the basis determined by the economics of operation of the particular units involved. It may even be desirable to spill a certain amount of water over the dam rather than operate the machines at full gate. This would be true in the case where the discharge from the plant is taken through a tailrace canal and excess flow reduces the head on the turbine and the loss in the conduit more than would be the case if the water were spilled over the dam into the main channel of the river. In certain cases, the question of the rate and time for spilling surplus water and its effect on over-all performance may result in increased output after the intermediate zone is passed.

System Reserve

The factor of system reserve capacity is one which should receive a great deal of attention and careful study to determine a reasonable margin for reserve to adequately protect the system against any shortage of power during sudden demand periods and at the same time avoid excessive waste of water due to carrying too much reserve in parallel with the system. This phase of operation introduces a still further burden on the operation staff due to the requirement of shutting down and starting up units at the proper time. It also introduces a serious responsibility on the part of the system load dispatchers, due to the necessity of maintaining sufficient capacity in service to care for the normal operating emergencies which would interfere seriously with rendering service, if such reserve capacity were not immediately available. The operation of any generating station or any generating equipment for reserve purposes requires the intimate knowledge gained from contact with the particular system in determining the proper amount and location of the system reserve.

Once these general requirements are established, the reserve can be allocated to plants best adapted to carry it and further studies made to decide the most economical manner in which this reserve can be maintained. All of these studies would usually divide the reserve into two classes, namely, that for immediate availability and second, for so-called delayed availability. Studies can be made of actual cost of carrying reserve capacity in any one plant or with any combination of units. On the same basis additional studies will indicate the desirability of operating units as synchronous condensers or merely as reserve capacity floating on the line. At most plants some saving can be secured by motoring the units from the line with the wheel gates tightly closed and the runner vented so that it is operating in air rather than in water. The difference between the cost of maintaining the reserve by these two methods and of having surplus units carrying light loads represents a very marked saving which can be effected if the element of availability can be secured.

The last element of economy to be considered is the relation of the output of one hydroelectric station with respect to other plants on the same stream, which is intimately tied up with local conditions, such as the reservoir capacity at the plant furthest up the stream, the distances between plants, the type and amount of pondage available and the characteristics of the stations themselves, with particular reference to the load factors for which they were designed and their relative discharge capacities. Each operating economy has its own peculiar problems affected by such local conditions and except for the value as relative information, the solution of this operating problem on any one system usually is not applicable directly to other systems.

It is of course self-evident that all of these factors have been given and are still being given a great deal of attention by the operating companies and by the operating engineers. The one element, however, which has seriously hampered the achievement of ideal economy of operation has been the necessity of depending entirely upon the human element.

The tendency to reduce operating forces to a minimum in order to make corresponding savings in operating costs, has greatly increased the duties and the responsibilities of the individual operators with the result that the operator's attention has been forcibly directed to the prime requirement of maintaining continuous service and the question of economy has been made a second consideration. The burden of maintaining accurate loading schedules and in fact, of giving careful attention to each of the factors outlined at the beginning of this article, will pass beyond the realm of possibility for manual operation unless con-

siderable increases in the operating staffs are made, combined with rigid supervision.

Automatic Control of Economic Load Division

With the development of automatic control equipment the whole aspect of these operating problems changes, since the human element no longer becomes the limiting factor. The introduction of the so-called "automatic operator," the development of which has been sponsored by I. P. Morris & De La Vergne, Inc., represents the application of a new principle to operating practise. By analyzing the economies of operation, preparing ideal schedules adapted to the particular system requirements, the application of specially designed automatic control equipment permits the rigid enforcement of these ideal schedules and eliminates the losses which result from the inability of operators to follow these schedules continuously.

One of the first opportunities to apply this new principle of operation was found at the Norwood plant of the Carolina Power & Light Company. Descriptions of this plant's operation have recently been published.[1] The problem presented in this case was somewhat different from the usual operating problem in that the three units in the station with an aggregate capacity of of 87,000 hp., consisted of two high-speed, large capacity units with relatively steep efficiency curves, and one unit of the slow-speed type with somewhat

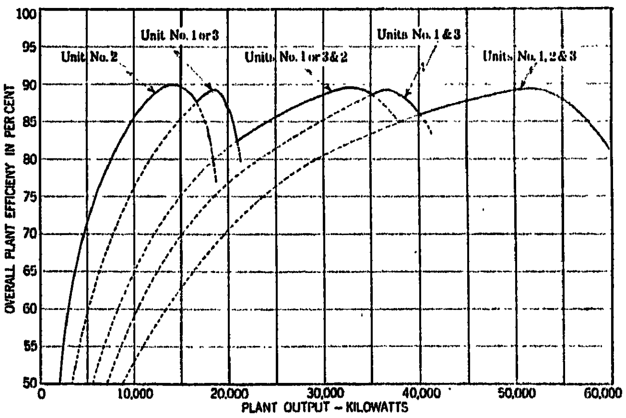

FIG. 1—OVER-ALL EFFICIENCY CURVE. NORWOOD DEVELOPMENT

smaller capacity, but having a relatively flat efficiency curve when compared with the other two units. By installing units of these different capacities, it was possible to secure a higher average efficiency for the plant over its entire range of output than would be possible if all three units were of the same high-speed characteristics.

The economic loading schedules for the proper distribution of load between units to maintain the maximum combined efficiency indicated a rather complex problem of operation. It was easily demonstrated that a slight departure from the proper loading schedule would result in an appreciable loss in efficiency. This plant therefore represented an ideal application for automatic load control equipment and after intensive studies and investigations upon the part of the staff of I. P. Morris & De La Vergne, Inc., it was felt that the problem could be solved very simply through the application of certain existing instruments which heretofore had not been used for this purpose but which could, with minor changes be adapted to fulfil the requirements at Norwood.

The equipment as actually installed, consists principally of a multiple bridge circuit, one side of each bridge consisting of a manually adjusted standard potential

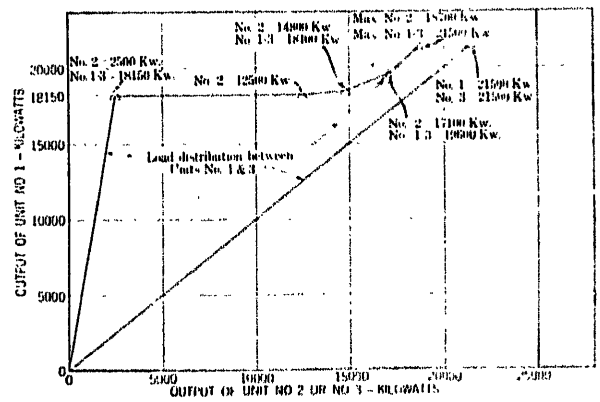

FIG. 2—CURVES SHOWING IDEAL LOADING SCHEDULE. NORWOOD DEVELOPMENT

and the other side, a potential in proportion to the unit output. By basing the standard potential relations upon the ideal schedule for load division between units, the balance would be secured, at which point the load on the various individual units would be brought to the standard as manually set, which in turn was in accordance with the desired load distribution between units. By this relatively simple scheme, the loading schedules could be maintained through the operation of a single dial and the economic load distribution effected between any combination of units in service. A number of additional attachments were incorporated in the control in order to provide more flexible operation, but these did not introduce any change in the basic principle upon which the control is designed.

Fig. 1, showing the over-all efficiency curve for the Norwood Development and Fig. 2, showing the ideal loading schedule for one unit with respect to the other, illustrate what can be accomplished by the application of automatic control to relieve the operators of the burdensome routine and at the same time, maintain the highest possible operating efficiencies on the station. Fig. 3 is the same as Fig. 1 except that points of actual operation, as taken from the log sheets, have been plotted. The circles show the results of manual operation while the triangles represent the operation after the automatic control was in service. The general curve drawn through the points of efficiency on manual

1. "Automatic Operator a Success," F. M. Nash, *Electrical World*, Aug. 25, 1930.

control, shows the trend and is based on the results obtained from a study of the integrated averages of kilowatt hours generated before and after the control was installed.

The approximate figures indicate that the production efficiency of the Norwood plant, in so far as its relation with the ideal operating curve is concerned, was approximately 90 per cent on manual control. After the development of the automatic operator and its installation at Norwood, the losses were materially reduced and

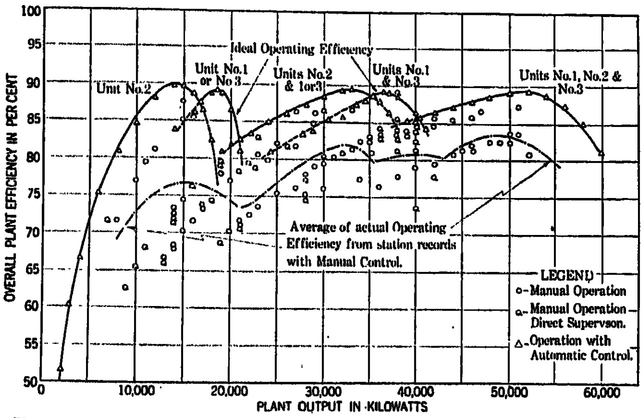

FIG. 3—CURVES SHOWING IDEAL OPERATING EFFICIENCY AS COMPARED WITH ACTUAL OPERATING EFFICIENCY UNDER MANUAL CONTROL AND AUTOMATIC CONTROL

the average operating efficiency was in excess of 96 per cent and was later increased to approximately 98 per cent for appreciable periods of time. The difference between the ideal operation, which would be represented as operation along the envelope curve in Fig. 1 and Fig. 3, and the actual results secured at Norwood, include all losses due to having the incorrect number of units in service as well as the losses introduced by maintaining system reserve capacity or minimum loads on the station for reserve purposes.

The actual loss incurred by incorrect distribution of the load between the units which were in service was found to be materially less than 1 per cent, and thus the operating efficiency of the Norwood Station, in so far as load division was concerned, has been consistently better than 99 per cent.

These figures have been taken from actual station records which are prepared daily in the general form as shown in Tables I and II. A detailed analysis of these efficiency log sheets enables the operating engineers to determine the reasons for production losses and permits them to direct attention upon the elimination of these losses with accurate records upon which to base their analyses.

The efficiency logs as shown in Tables I and II list two losses, namely, the distribution loss and the unit loss. The distribution loss concerns only the question of economic load distribution between units and the economic combination of units in service. The unit loss represents the loss incurred due to the operation at points other than at the maximum efficiency of the unit or combination of units. Thus, if the units are operated with the proper load distribution and are also operated at some point of maximum efficiency on the envelope curve in Fig. 1, the distribution loss would be zero, and the unit loss would also be zero, giving a production efficiency of 100 per cent. In cases, however, where the load dispatched to Norwood is at some other point on the over-all efficiency curve, then even if the load is economically distributed between the units in service and the corresponding distribution loss is zero, the unit loss will be introduced due to operating the plant at a lower efficiency than its maximum. The difference in discharge or possible output between the actual point of operation and point of maximum efficiency has been established as this unit loss. In each of the log sheets, both these losses are given and a notation is made of the distribution efficiency as well as the unit efficiency, the product of the two being the production efficiency.

In order to simplify the work of the load dispatcher, the curve shown as Fig. 4 was prepared representing the station output with respect to station discharge, upon which has been superimposed radial lines representing uniform increments of the kilowatts obtainable for each cu-ft-per-sec. of water through the station under the rated head at which the plant normally operates. These radial lines intersect the power-discharge curves at various points and both the load dispatchers and station operators can see at a glance the zones of desirable operation, and where system conditions permit, the

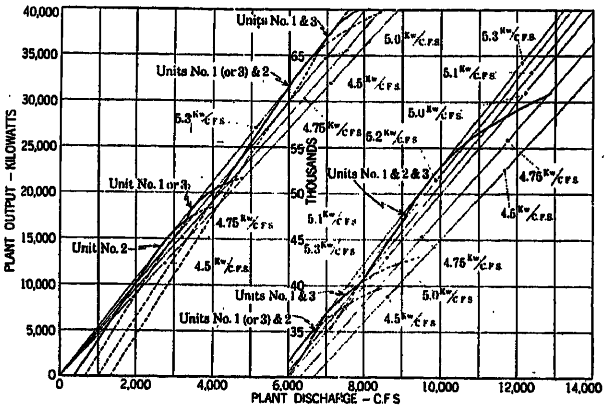

FIG. 4—CURVES SHOWING STATION OUTPUT VS. STATION DISCHARGE—NORWOOD DEVELOPMENT

Lines of kilowatts per second-feet included

maximum efficiency loads are dispatched to the Norwood Station.

By means of these curves and log sheets, when combined with the assurance that whatever load is dispatched to the Norwood Station will be carried in the most economic manner possible, the system operators and load dispatcher were provided with a more efficient tool with which to work, with the result that the operating efficiencies at Norwood have reflected exceptionally large savings to the power company over and above the

TABLE I
CAROLINA POWER & LIGHT COMPANY
DAILY LOAD EFFICIENCY DATA

Plant Norwood — 24 hours ending August 19, 1929

Time	No. 1 unit Kw.	No. 1 unit Water used	No. 1 unit Eff. loss	No. 2 unit Kw.	No. 2 unit Water used	No. 2 unit Eff. loss	No. 3 unit Kw	No. 3 unit Water used	No. 3 unit Eff. loss	Totalkw. generated	Total water used	Possible kw.	Production eff. kw. losses distr.	Production eff. kw. losses unit	Production eff. kw. losses total	By-pass discharge sec. ft.	Remarks
12 m.n.	0	0	0	12,000	2,300	213	0	0	0	12,000	2,300	12,000	0	213	213	0	No. 2 unit—night load—LD
1 a.m.	0	0	0	12,000	2,300	213	0	0	0	12,000	2,300	12,000	0	213	213	0	No. 2 unit—night load—LD
2 a.m.	0	0	0	12,000	2,300	213	0	0	0	12,000	2,300	12,000	0	213	213	3,060	No. 2 unit—night load—LD
3 a.m.	0	0	0	13,000	2,470	115	0	0	0	13,000	2,470	13,000	0	115	115	3,060	No. 2 unit—night load—LD
4 a.m.	0	0	0	13,000	2,470	115	0	0	0	13,000	2,470	13,000	0	115	115	3,060	No. 2 unit—night load—LD
5 a.m.	0	0	0	13,000	2,470	115	0	0	0	13,000	2,470	13,000	0	115	115	3,060	No. 2 unit—night load—LD
6 a.m.	0	0	0	10,000	1,980	513	0	0	0	10,000	1,980	10,000	0	513	513	0	6:10 a.m. No. 1 + 2 units on increasing load
7 a.m.	13,000	2,640	939	7,000	1,500	965	13,000	2,640	939	33,000	6,780	35,800	2,800	2,843	5,643	0	6:30 a. m. No. 3 on reserve for day load
8 a.m.	16,500	3,220	501	7,000	1,500	965	16,500	3,220	501	40,000	7,940	40,600	600	1,967	2,567	0	Day load increasing
9 a.m.	18,000	3,420	57	8,000	1,670	967	18,000	3,420	57	44,000	8,510	44,000	0	981	981	0	Day load normal
10 a.m.	18,000	3,420	57	9,000	1,830	717	18,000	3,420	57	45,000	8,670	45,000	0	831	831	0	Day load normal
11 a.m.	18,000	3,420	57	12,000	2,300	213	18,000	3,420	57	48,000	9,140	48,000	0	327	327	0	Day load normal
12 m.	11,000	2,330	1,302	0	0	0	11,000	2,330	1,302	22,000	4,660	23,400	1,400	2,604	4,004	0	Noon drop No. 2 retired for economy
1 p.m.	16,500	3,220	501	0	0	0	16,500	3,220	501	33,000	6,440	34,100	1,100	1,002	2,102	0	Reserve for increasing load
2 p.m.	18,000	3,420	57	7,000	1,500	965	18,000	3,420	57	43,000	8,340	43,000	0	1,079	1,079	0	No. 2 on for additional reserve
3 p.m.	18,500	3,500	0	15,000	2,820	0	18,500	3,500	0	52,000	9,820	52,000	0	0	0	0	Nos. 1, 2 and 3 on max. produc. effi.
4 p.m.	18,000	3,420	57	10,000	1,980	513	18,000	3,420	57	46,000	8,820	46,000	0	627	627	0	No. 2 held for system reserve
5 p.m.	18,000	3,420	57	10,000	1,380	513	18,000	3,420	57	46,000	8,820	46,000	0	627	627	0	No. 2 held for system reserve
6 p.m.	17,000	3,300	424	7,000	1,500	965	0	0	0	24,000	4,800	24,200	200	1,389	1,589	0	No. 3 retired for economy
7 p.m.	7,000	1,730	2,134	7,000	1,500	965	0	0	0	14,000	3,230	16,800	2,800	3,099	5,899	0	No. 1 and 2 on night load
8 p.m.	12,000	2,490	1,147	7,000	1,500	965	0	0	0	19,000	3,910	20,200	1,200	2,112	3,312	0	Nos. 1 and 2 on night load
9 p.m.	9,000	2,030	1,718	7,000	1,500	965	0	0	0	16,000	3,530	18,600	2,600	2,683	5,283	0	Nos. 1 and 2 system reserve stormy
10 p.m.	7,000	1,730	2,134	7,000	1,500	965	0	0	0	14,000	3,230	16,800	2,800	3,099	5,899	0	Nos. 1 and 2—system reserve—stormy
11 p.m.	7,000	1,730	2,134	7,000	1,500	965	0	0	0	14,000	3,230	16,800	2,800	3,099	5,899	0	Nos. 1 and 2—system reserve—stormy
12 p.m.	7,000	1,730	2,134	7,000	1,500	965	0	0	0	14,000	3,230	16,800	2,800	3,099	5,899	0	Nos. 1 and 2—system reserve—stormy
Total kw.	249,500	50,170	15,410	207,000	41,570	13,757	183,500	35,430	3,585	640,000	127,170	661,100	21,100	32,752	53,852	12,240	
Total kw-h.	250,000			220,000			180,000			650,000							Production effici. = 92.3

TABLE II

CAROLINA POWER & LIGHT COMPANY
DAILY LOAD EFFICIENCY DATA

Plant Norwood | 24 hours ending August 6, 1929

Time	No. 1 unit			No. 2 unit			No. 3 unit			Totalkw. gener-ated	Total water used	Possible kw.	Production eff. kw. losses			By-pass dis-charge sec. ft.	Remarks
	Kw.	Water used	Eff. loss	Kw.	Water used	Eff. loss	Kw.	Water used	Eff loss				distr.	unit	total		
12 m.n.	0	0	0	17,000	3,310	576	0	0	0	17,000	3,310	17,000	0	576	576	0	Light load most effi. on No. 2
1 a.m.	0	0	0	15,000	2,820	0	0	0	0	15,000	2,820	15,000	0	0	0	0	Light load most effi. on No. 2
2 a.m.	0	0	0	16,000	3,030	89	0	0	0	16,000	3,030	16,000	0	89	89	0	Light load most effi. on No. 2
3 a.m.	0	0	0	16,000	3,030	89	0	0	0	16,000	3,030	16.000	0	89	89	0	Light load most effi. on No. 2
4 a.m.	0	0	0	16,000	3,030	89	0	0	0	16,000	3,030	16,000	0	89	89	0	Light load most effi. on No. 2
5 a.m.	0	0	0	16,000	3,030	89	0	0	0	16,000	3,030	16,000	0	89	89	0	Light load most effi. on No. 2
6 a.m.	0	0	0	15,000	2,820	0	0	0	0	15,000	2,820	15,000	0	0	0	0	Light load most effi. on No. 2
7 a.m.	18,500	3,500	0	11,000	2,150	416	18,500	3,500	0	48,000	9,150	48,000	0	416	416	0	Increasing load Nos. 1 and 3 on max. effi.
8 a.m.	18,500	3,500	0	13,000	2,470	115	18,500	3,500	0	50,000	9,470	50,000	0	115	115	0	Increasing load Nos. 1 and 3 on max. effi.
9 a.m.	19,000	3,600	0	15,000	2,820	0	19,000	3,600	0	53,000	10,020	53,000	0	0	0	0	100 % product. effi. on all units
10 a.m.	19,000	3,600	0	15,000	2,820	0	19,000	3,600	0	53,000	10,020	53,000	0	0	0	0	100 % product. effi. on all units
11 a.m.	19,000	3,600	0	15,000	2,820	0	19,000	3,600	0	53,000	10,020	53,000	0	0	0	0	100 % product. effi. on all units
12 m.	19,000	3,600	0	15,000	2,820	0	19,000	3,600	0	53,000	10,020	53,000	0	0	0	0	100 % product. effi. on all units
1 p.m.	0	0	0	15,000	2,820	0	19,000	3,600	0	34,000	6,420	34,000	0	0	0	0	Noon drop. No. 1 retired for economy
2 p.m.	19,000	3,600	0	15,000	2,820	0	19,000	3,600	0	53,000	10,020	53,000	0	0	0	0	100 % product effi. on all units
3 p.m.	19,000	3,600	0	15,000	2,820	0	19,000	3,600	0	53,000	10,020	53,000	0	0	0	0	100 % product effi. on all units
4 p.m.	19,000	3,600	0	15,000	c 2,820	0	19,000	3,600	0	53,000	10,020	53,000	0	0	0	0	100 % product effi. on all units
5 p.m.	19,000	3,600	0	0	0	0	19,000	3,600	0	38,000	7,200	38,000	0	0	0	0	100 % product effi. on units Nos. 1 and 3
6 p.m.	19,000	3,600	0	0	0	0	19,000	3,600	0	38,000	7,200	38,000	0	0	0	0	100 % product effi. on units Nos. 1 and 3
7 p.m.	15,000	2,980	734	0	0	0	0	0	0	15,000	2,980	15,800	800	734	1,534	0	Inefficient load on
8 p.m.	19,000	3,600	0	0	0	0	0	0	0	19,000	3,600	19,000	0	0	0	0	Max. effici. load on No. 1
9 p.m.	19,000	3,600	0	15,000	2,820	0	0	0	0	34,000	6,420	34,000	0	0	0	0	Max. effici. night load on Nos. 1 and 2
10 p.m.	0	0	0	15,000	2,820	0	0	0	0	15,000	2,820	15,000	0	0	0	0	Load dropping—on No. 2 for effici.
11 p.m.	0	0	0	12,000	2,300	213	0	0	0	12,000	2,300	12,000	0	213	213	0	Load dropping—most effici. on No. 2
12 p.m.	0	0	0	10,000	1,980	513	0	0	0	10,000	1,880	10,000	0	513	513	0	Load dropping most effici. on No. 2
Total kw.	261,000	49,580	734	290,000	54,860	1,613	227,000	43,000	0	778,000	147,440	778,000	800	2,347	3,147	0	Load dropping most effici. on No. 2
Total kw-h.	270,000			300,000			210,000			780,000							Production effici. = 99.6

very best that could possibly be obtained with manual operation.

Automatic Control of Economic Number of Units in Service

The automatic control of the Norwood Station was only the starting point for the application of automatic economy control to power generating stations. In each of the new plants undertaken, new problems arose which have so far been successfully cared for by the application of automatic control equipment.

One of the most interesting developments which has recently completed the first few months of successful operation, has been the Morony Development of the Montana Power Company. In line with the general desire to improve operation, and finding that the Morony plant was best adapted for this work, automatic frequency control equipment was installed as part of the hydraulic turbine contract. This station, however, had two units of the same characteristics and it was estimated that the requirement for maintaining frequency on the Montana system would call for the continuous operation of two units through a range of output from one-half to three-quarters of their full-load rating. As the load on that system is subject to variations which are not easily predicted, the question immediately arose in regard to the loss of efficiency due to operating two units below one-half of their individual capacities where the load could be more efficiently carried on a single unit.

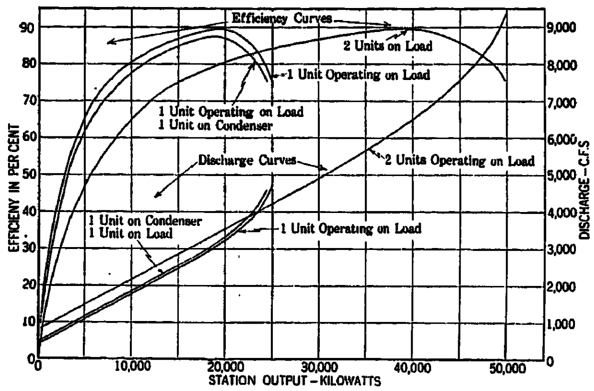

Fig. 5—Automatic Operator for Montana Power Co., Morony Development

Station curves showing performance with one and two units in operation

With the application of automatic frequency control to this plant, a further step was made in the development of automatic economy control by arranging special equipment which would automatically transfer one unit from operating on load to operation as a synchronous condenser when the point had been reached where one unit alone could carry the particular load of the station more efficiently than two units. Fig. 5 shows the curve of over-all plant efficiency with respect to plant output for both one and two units. It may be seen very readily that below an output of about 23,000 kw., it is more efficient to run a single unit than it would be to operate both units. The question immediately arose as to whether it would be desirable to signal the operator at this point and have him shut down one unit and carry the load on the remaining unit. However, as the immediate availability of this surplus unit was of great value in supplying sudden demands for load, it was found that instead of shutting down one unit, it could very conveniently be transferred automatically to synchronous condenser operation. The first unit was arranged to pick up whatever load was required as well as to supply the power required to drive the other unit as a synchronous condenser. By the use of very efficient automatic air vents, the power required to drive the unit as a synchronous condenser was held to very small limits and from actual tests, the curve shown for one unit operating on load with one unit as a condenser gives a loss of less than 2 per cent below the efficiency of one unit operating alone. Provision was also made for this reserve unit to come back on load automatically when it was required either at a very slow rate for normal service, or at a very rapid rate if it was required for emergency conditions.

Fig. 6 represents the economic analyses of this station, with the savings effected by this control plotted with respect to station output. Approximately 2,400 kw. are saved by the operation of one unit on condenser and one unit on load based upon the utilization of the same flow as would be required for two units carrying the same load. This saving in kilowatts can be translated into money, and for this purpose, an arbitrary

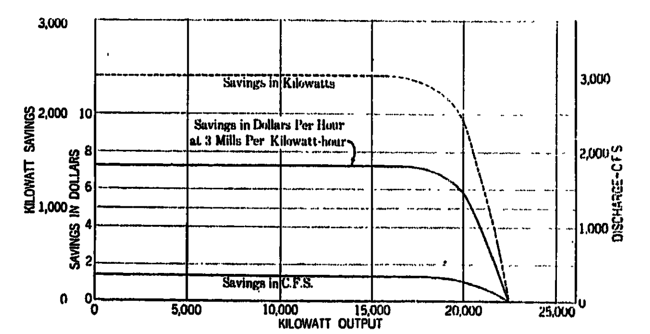

Fig. 6—Automatic Operator for Montana Power & Light Co.—Morony Development

Station curves showing savings in kilowatts, dollars and discharge against kilowatt output for automatic operation

figure of three mills per kw. hr. was used. According to the latest studies, this represents slightly over $7.00 per hr. saving with this very low power rate for each hr. that the plant is operated below an output of 18,000 kw. Since storage facilities are available, these same savings can be translated into savings in discharge, which is the third curve shown on this figure.

The possibilities of extending this type of control to other applications is virtually unlimited at present, and installations are now under way for similar equipment in plants containing as many as four units. In

this case, the savings increase materially above those shown for the Morony Development in Fig. 6, since the possibilities of saving are proportionately larger.

This feature introduces another phase of operation, namely, the economic carrying of system reserve capacity through the operation of one or more units in the station as synchronous condensers combined with automatic control equipment to make them immediately available if they are required for service either as the result of a normal increase in load occurring at the particular time, or due to system disturbances requiring additional generating capacity at once, in which case the rate at which these reserve units will pick up the load will be very much more rapid. It is thus possible to allocate the system reserve to hydroelectric plants in which surplus capacity is available and by the proper use of automatic control equipment have this reserve capacity automatically available without the necessity of any operation on the part of either the load dispatchers or of the operators themselves.

The actual performance of this automatic frequency control equipment, combined with the elements of automatic economy control to effect both the economic load distribution and the maintenance of the economic combination of units in service, has been very gratifying indeed. The control at Morony has been in service for several months and has been very effective indeed in stabilizing the frequency under rather severe service conditions. The type of load on this system fluctuates greatly, due to its inherent characteristics, and to the self-regulating characteristics of the system itself being relatively small. The automatic transfer from load to condenser and from condenser to load of the reserve unit is effected very easily and without any attention being required on the part of the operator. A slightly revised operating procedure based upon the new conditions, was inaugurated by the load dispatchers and the water balance between the various plants was found to be more easily maintained than with the previous condition of hand regulation of the speed.

Combined Operation of Series of Plants

These same principles which have been outlined in describing the application of automatic economy control to individual plants, are readily adaptable to the operation of groups of plants. The inter-relation of the loading on different stations, particularly with regard to a series of plants on a single river, has the effect of making the series of plants perform as the equivalent of a single over-all development. The actual operation of such a system when combined with other devices to make use of pondage and peak load requirements, offers a very effective solution for the difficulties in operating such stations. There are several different methods which can be employed to effect this type of operation, each of which may be more desirable, depending upon the local requirements, the distances between the plants, and the general conditions existing in the particular application under consideration.

Combined Operation of Steam and Hydroelectric Plants

The automatic economy control applied to groups of hydroelectric plants can also be applied very readily to a combination of steam and hydroelectric plants whereby the hydro plant can maintain a base load during high flow seasons, leaving the steam plant to take the fluctuations in load, while for periods where surplus water is not available, the hydroelectric plant can more readily supply the fluctuating load leaving the steam plant to operate on fixed output.

This general scheme of operation has been suggested in a number of papers, but by the use of automatic economy control it can be made a reality and most of the benefits from the combined operation of such stations can actually be secured.

The application of automatic economy control to electric power generation requires an intimate knowledge of system characteristics as well as the prime mover characteristics. The success of automatic economy control installations can only reach the highest degree through complete cooperation of the manufacturer with the operating companies and by maintaining an impartial attitude in regard to the equipment to be used, its application and its limits. The engineering of design and application must be carried out with these principles in view in order to secure the ultimate aim of this equipment, namely, the highest efficiency of power generation possible with the installed equipment.

Discussion

H. A. Von Eiff: Referring to the section covering condenser operation, it is interesting to state that we have found a large gain in economy at the Holtwood plant by operating one unit as a synchronous condenser on both the 25- and 60-cycle systems.

The Holtwood plant prior to 1924 had eight 25-cycle units, seven of which were double-runner units and one a single-runner unit. The single-runner unit was installed in 1914 and in 1921, when the flow of the Susquehanna river was at a low stage, this unit was used as a synchronous condenser solely for power-factor correction to permit the plant to shut down. Since 1921 when the flow necessitates a complete shut down this unit is used for condenser operation and has operated very satisfactorily. It requires approximately 650 kw. or 5.4 per cent of the rated capacity to operate this unit as a condenser with gates closed and vacuum broken and this loss is small compared to the gain in economy and peak service.

A study was made to determine the gain in output by operating one unit as a condenser which would be available for spare capacity and one unit carrying load when the load on the hydro plant could be carried on one unit but the capacity of two units would be needed for spare. This study showed a saving of 150 to 300 cu. ft. per sec., depending on the head and the load carried, or a gain of approximately 500 to 1,000 kw. This operation is entirely by manual control and the governor on the condenser unit is adjusted so that the unit will pick up load if the frequency drops.

In 1934 two 60-cycle single-runner units were installed in the Holtwood plant and the gain in economy from operating a 25-cycle unit as a condenser led to making a study of synchronous condenser operation on one of the two 60-cycle units for loads of one-unit capacity but requiring two units for spare capacity. The operation proved satisfactory when the tailrace elevation was below the runner and the saving from condenser operation

on these two units varied from 500 to 700 cu. ft. per sec. and from approximately 1,500 to 2,300 kw., or from 13 to 27 per cent of the load, depending on the head and load carried. The large gain in economy on these units compared to the 25-cycle units is due to the fact that they have higher specific speed, or lower part gate efficiencies. It is also interesting to note that the energy required to operate these units as condensers with gates closed and vacuum broken amounts to approximately 400 kw. or 3.3 per cent of rated capacity.

Carroll F. Merriam: A most valuable point brought out by this paper is the fact that although hydro units have approached the ultimate in maximum efficiency, it does not indicate that the ultimate in economy in the use of water has by any means been reached. It is often heard that because hydro units have now been built with efficiencies so near 100 per cent, little improvement can be expected in hydro development. The list of nine general problems included in this paper is in itself sufficient evidence that maximum efficiency is not the sole measure of the success of the hydraulic turbine designer.

In addition to these nine, there are two others which come readily to mind and which offer fruitful fields for study where favorable conditions exist. The first is the possibility of making use of flood waters by means of head increasers such as the ejector turbine, and the backwater suppresser. It is entirely possible that when the principles of the ejector are better understood there will be found many applications for these means of getting increased capacity during times of flood. Another problem which may at first appear paradoxical is the economy of spilling water over a fixed crest dam at times of insufficient flow. When conditions are particularly propitious, that is, with a sharp peak during the early hours of hydro generation, a short spillway, and especially if in order to accommodate the steam plants, the pond is drawn down weekly so that the maximum elevation is reached but once a week, there can be shown an appreciable saving by securing higher average head even though the pond is allowed to overflow a few tenths of a foot.

The importance of test data should receive emphasis since the incidental information gathered at the time of an acceptance test may easily pay for the entire cost. The curves derived from the tests on the units at the Holtwood plant of the Pennsylvania Water & Power Company, are frequently used as the basis of economic studies leading to improved operation. Attention should also be given to supplementing the official tests with comparative tests made by an index method so that the range of conditions covered by the tests in which the water measurements are carefully made may be extended to cover extraordinary values of head which could not be obtained at the time of the test itself. There are several methods that are now being developed for making comparative measurements of water, which methods can be calibrated at the time of acceptance tests, and used for many purposes afterwards by the plant operators or test department.

The author's statement that it may even be desirable to spill water over the dam rather than operate the machines at full gate, suggests that we look beyond the "station over-all performance" which the author states is "the efficiency relation which is of most value for power plant operation" and consider the economy of the project as a whole. This is particularly true where there is an inadequate tailrace. In this connection it should be kept in mind that excess water passing through a turbine not only lowers the head on the turbine itself but also that of the other turbines in the same plant. An example of this was found at Holtwood where by reducing the output of two turbines below their own points of maximum output, the send out of the station as a whole was increased about 400 kw.

In regard to maintaining maximum head on a single hydro plant feeding into a large system, it is often considered the best economy in times of insufficient flow, to give the steam station a flat schedule and take all of the swings on the hydro. Any inequality in the hydro load during the day will draw down the pond and cause the plant to suffer a consequent loss. To determine the economy of such practise involves a knowledge of steam plant conditions and the cost of carrying the swinging load by steam. This is exceedingly complicated, and although it is doubtful if it should prove economical to carry steady load on a run of river plant, nevertheless system operators should not be unmindful of the loss in economy. It is entirely possible that some compromise would be found to give the best results in the end.

An interesting phase of interconnected plant economics, not mentioned in the paper, is where two plants are close together on the same river and have overlapping head. Let us assume that the upper of the two plants has a pond about three times as large as the lower, and furthermore, that the lower has a poor tailrace whereas the upper discharges directly into the pond of the lower with very slight loss of head between the two plants. At time of low flow there are three distinct methods of operation, to say nothing of many combinations which can be overlooked for the present. The first is to carry base load on the upper plant which means that the average forebay will be maintained at as high level as possible. The second is that both plants would share the load in such a manner that both discharge the same amount of water at all times. This means that the lower pond may be maintained always full and that the loss in head between the plants will be a minimum. The third method is to have the lower plant carry the base in which case the average tailwater will be lowered on account of a more steady discharge during the hours of hydro operation.

It is a very nice problem to determine the most economical method and although it appears from knowledge of the situation that the lower plant should carry the base, the final solution will probably be some form of compromise.

It will be noted that the estimates given of the savings realized by the use of the automatic operator are based upon hourly integrated loads. It should be pointed out that this is at least conservative since the difference between using integrated values and instantaneous values taken at random would tend to make the savings appear to be *less* than they really are. The reason is that any variation from the average values during the hour under manual control will tend to give actually less efficiency than that corresponding to the average loading for the hour. Under automatic control the efficiency is maintained at the theoretical maximum by supervision every two seconds. On the other hand, it does not stand to reason because Norwood showed a difference of about 10 per cent between the efficiency under manual operation and the theoretical maximum, that this is typical of hydro plants in general. The conditions at this plant, having units of different characteristics, are such that it would be particularly hard for the operators to appreciate the value of holding their units to a fixed loading schedule. In a plant where all the units are alike it is much easier for the operators to be educated to maintain equal loadings on all units. Although it is difficult to train operators to pay strict attention to unit loading, it is hard to believe that the resulting loss will ordinarily amount to as much as ten per cent.

Reference is made to the fundamental principles of economic loading as presented in a paper by Rogers and Moody at the Third Hydroelectric Conference in 1925, but it is not stated clearly how these principles have been applied in the case of the problem at hand. A very simple method of constructing economic loading schedules has been employed by the Pennsylvania Water & Power Company and it would probably be of interest to the hydroelectric industry to know how easily such schedules can be laid out from given efficiency curves.

The author has also omitted to mention the course of action to be taken when the variation in head on the plant is sufficient to be considered.

It is undoubtedly a considerable advance in power plant design to have units of dissimilar characteristics, but considerable care must be taken in selecting the units in order to properly balance all of the factors and thus avoid over emphasis upon any one element. For example, if high combined efficiency were the only consideration, it would have been better at Norwood to have made No. 2 unit somewhat smaller. It can be seen by reference to Fig. 1 that the "Unit 2" curve would have been shifted somewhat to the left, "Unit No. 1 or 3" curve would have remained where it is, but "Unit No. 1 or 3 with Unit No. 2" curve would also be shifted to the left to fill in the deep gap, or inefficient zone, between. On the other hand, the cost per horsepower would certainly have been increased and the capacity of the plant at time of high water would have been reduced.

Damper Windings for Water-Wheel Generators

BY C. F. WAGNER*
Member, A. I. E. E.

Synopsis.—The severity of unsymmetrical system faults is affected by the negative sequence impedance of the connected machines. These impedances in turn depend largely upon the character of damper windings. The paper discusses the effect of amortisseur or damper windings upon both the real and reactive components of the negative sequence impedance. Machines without damper windings possess the highest negative sequence reactance and from this viewpoint are the most desirable, but machines with high-resistance damper windings possess the highest negative sequence resistance. Calculations show that combining the effect of resistance and reactance, the high-resistance damper is more desirable.

In the event of system oscillations low-resistance copper damper windings produce the greatest damping of the mechanical movement. However, this effect is unimportant during and following a system fault except in the exceptional, rather rare case in which the system is so constituted that pull-out takes place as a result of compound oscillations following a disturbance.

Consideration is also given to a special type of double deck damper winding.

* * * * *

INTRODUCTION

AMORTISSEUR or damper windings have been installed in water-wheel generators in the past only when particular requirements, such as increased starting torque for automatic operation, demanded. In general, water-wheel generators in manually controlled power stations were not equipped with damper windings. The recent emphasis placed upon stability problems and power limits has raised the question as to whether or not some form of damper winding was desirable from stability considerations alone. Some have argued that inasmuch as stability problems involve rotor oscillations and since it is known that the installation of damper windings facilitates the operation of engine-driven generators, it follows that dampers should ameliorate instability conditions. The problem cannot be reduced to such a simple simile. It is the purpose of the present article to discuss some of the factors affecting the choice of damper windings for water-wheel generators.

I. NEGATIVE SEQUENCE IMPEDANCE

It has been shown by Evans and Wagner[1] that any unbalanced fault in a symmetrical† power system can be represented, through the application of the "method of symmetrical components," by means of a symmetrical set of impedances connected in shunt at the point of fault; thus converting the unbalanced fault to a symmetrical impedance load which is more amenable to solution. For the simple system shown in Fig. 1A consisting of a generator and a transmission line, with transformers at each end, feeding into a system, the equivalent symmetrical system for a line-to-line fault on the high tension bus at the generating end is shown in Fig. 1B. The single line diagram of Fig. 1c shows the synthesis of the shunt impedances, which are all negative sequence impedances. For the transformers and line the negative sequence impedances are the same as for the positive sequence, but for generators they are different. It follows, therefore, that by the aid of this conception and a knowledge of the negative sequence impedance of the generator, the synchronizing power between the voltages at the two ends of the system can be determined by a solution of the equivalent network. Similar relations are true for other kinds of faults. These may involve the zero sequence impedances of the system, but for delta-star transformer connections the zero sequence impedance of the generator does not enter the problem.

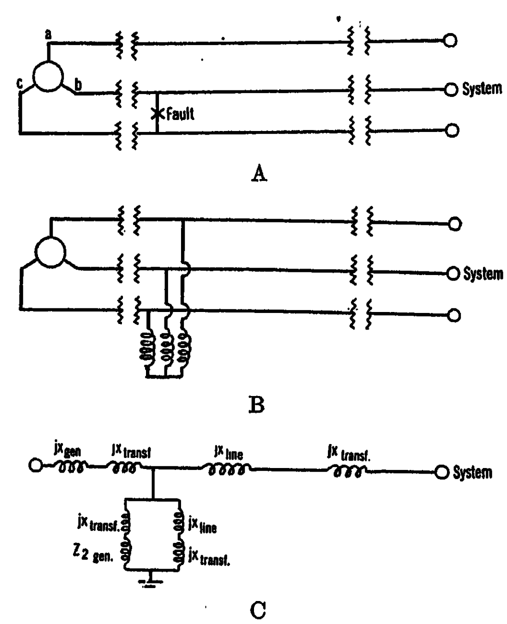

FIG. 1—REDUCTION OF UNBALANCED SYSTEM CONDITION CAUSED BY LINE-TO-LINE FAULT TO ITS EQUIVALENT SINGLE-LINE EQUIVALENT AND SHOWING THE SYNTHESIS OF THE EQUIVALENT SHUNT IMPEDANCE

A. Line-to-line fault on high-tension bus at generating end.
B. Symmetrical equivalent of (A)
C. Single line equivalent of (B)

What is the nature of this "negative sequence

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1. For references see Bibliography.

†Symmetrical is used here to describe a system that has the same characteristics and constants viewed from any phase.

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impedance?" The method of symmetrical components involves the resolution of three unsymmetrical currents or voltages into, first a set of three symmetrical currents or voltages whose instantaneous values reach their maxima in the order *a b c* (positive sequence); second, a set of symmetrical currents or voltages whose values reach a maximum in the order *a c b* (negative sequence); and third, a set of three currents or voltages which are in phase (zero sequence). Now while all of these vectors rotate in the same direction, when applied to a phase wound machine, the positive sequence produces a field rotating synchronously in the same direction as the rotor; the negative sequence a field rotating synchronously in the opposite direction, and the zero sequence a more complicated field, which is determined by differential leakages since the fundamental space distribution of the three phases just cancel one another. The negative sequence impedance of a machine is the impedance offered to the flow of negative sequence current, that is, it is the negative sequence voltage across the machine when one unit

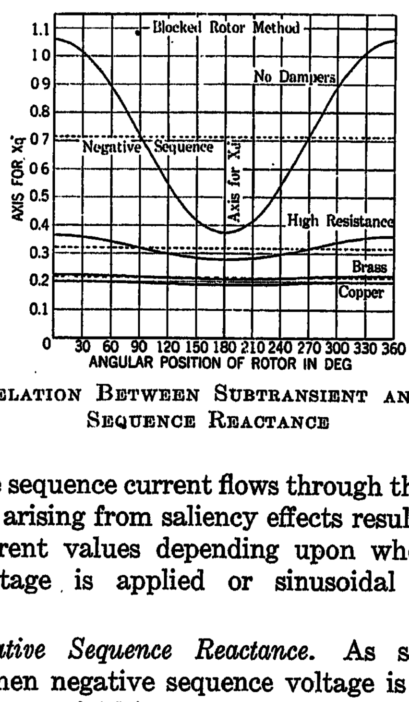

FIG. 2—RELATION BETWEEN SUBTRANSIENT AND NEGATIVE SEQUENCE REACTANCE

of negative sequence current flows through the machine. Distortion arising from saliency effects results in somewhat different values depending upon whether sinusoidal voltage is applied or sinusoidal current is circulated.

a. Negative Sequence Reactance. As stated previously, when negative sequence voltage is applied to the armature, a field is set up which rotates with synchronous velocity in a direction opposite to that of the rotor. This field sets up currents of double system frequency in the rotor. Now the subtransient reactances may be measured by blocking the rotor, with the field winding short-circuited, and applying a single-phase alternating voltage across two terminals of the armature. The reactance per phase measured in this manner varies with the position of the rotor. If the machine is not equipped with damper windings the variation is very great for when the axis of the rotor coincides with the axis of the pulsating field, the field winding constitutes a short-circuited secondary, producing a low impedance, but when the two axes are in quadrature, the impedance is merely that determined by the exciting current and is quite high. The upper curve in Fig. 2 shows these subtransient reactances plotted as a function of the angular position of the rotor. For the negative sequence measurement a similar phenomena is involved except that the rotor is rotating with double frequency with relation to the field set up by the applied voltage and is taking successively all the possible positions used in determining the subtransient reactance. One would expect, therefore, the negative sequence reactance to be some kind of a mean between the maximum value of subtransient reactance, x_q'', and the minimum value, x_d''. Park and Robertson[2] give for this value, when the circuit has a large value of reactance in series

$$x_2 = \frac{1}{2}(x_d'' + x_q'') \qquad (1)$$

The straight lines in Fig. 2 show the test results obtained for the imaginary component of Z_2, that is, the negative sequence reactance.

When low-resistance damper windings are added x_d'' is reduced somewhat because the damper winding is more closely associated with the air gap flux than the field winding and does not permit so much leakage but x_q'' is reduced greatly because the damper winding constitutes a short-circuited secondary with a relatively small leakage, whereas without a damper the reactance is determined by the exciting current. The reactances in the two axes, x_d'' and x_q'', are very nearly equal as is shown by the curve for this case in Fig. 2. It follows therefore that the negative sequence reactance is also very nearly equal to these values.

As the resistance of the damper winding is increased, little effect is at first discernible upon the reactance component of Z_2 because the resistance drop in the rotor circuit is in quadrature to the leakage reactance drop.

Interpreted in terms of the equivalent circuit of Fig. 1, the higher the negative sequence reactance, the greater will be the shunt impedance and the synchronizing power during the fault. This results in increased power limits.

b. Negative Sequence Resistance. The power associated with the negative sequence current may be expressed as a resistance times the square of the current. This resistance will be designated the "negative sequence resistance." For a machine with no dampers the only source of loss is in the armature and field resistances, eddy currents and iron loss. The copper loss in the armature and field is very small as is also the iron and eddy loss in the armature, but the iron and eddy loss in the rotor may reach quite high values. Copper damper windings provide a lower impedance path for the eddy currents and hinder the penetration of flux into the pole structure. The relatively low resistance of this path results in a smaller negative sequence resistance. For higher resistance

dampers, the negative sequence resistance increases to a point beyond which the larger resistance diminishes the current in the rotor circuits sufficiently to decrease the loss.

A large negative sequence resistance enables more power to be absorbed during the fault so that the decrease in power output is not as great, resulting in less acceleration and a greater stability limit. These considerations, manifestly, do not apply to synchronous condensers; because since they are usually connected to the receiving end of the line and usually retard during a fault, a high-resistance damper merely accentuates this effect and reduces the stability limit.

The following test results of negative sequence impedance illustrate the effect of the damper material for a 5,000 kv-a. condenser.

Material	Negative sequence impedance in per unit of machine rating
Copper................	$0.026 + j\,0.195$
Brass..................	$0.045 + j\,0.195$
High resistance.........	$0.12 \quad + j\,0.20$
No dampers............ (But with damper slots)	$0.045 + j\,0.75$

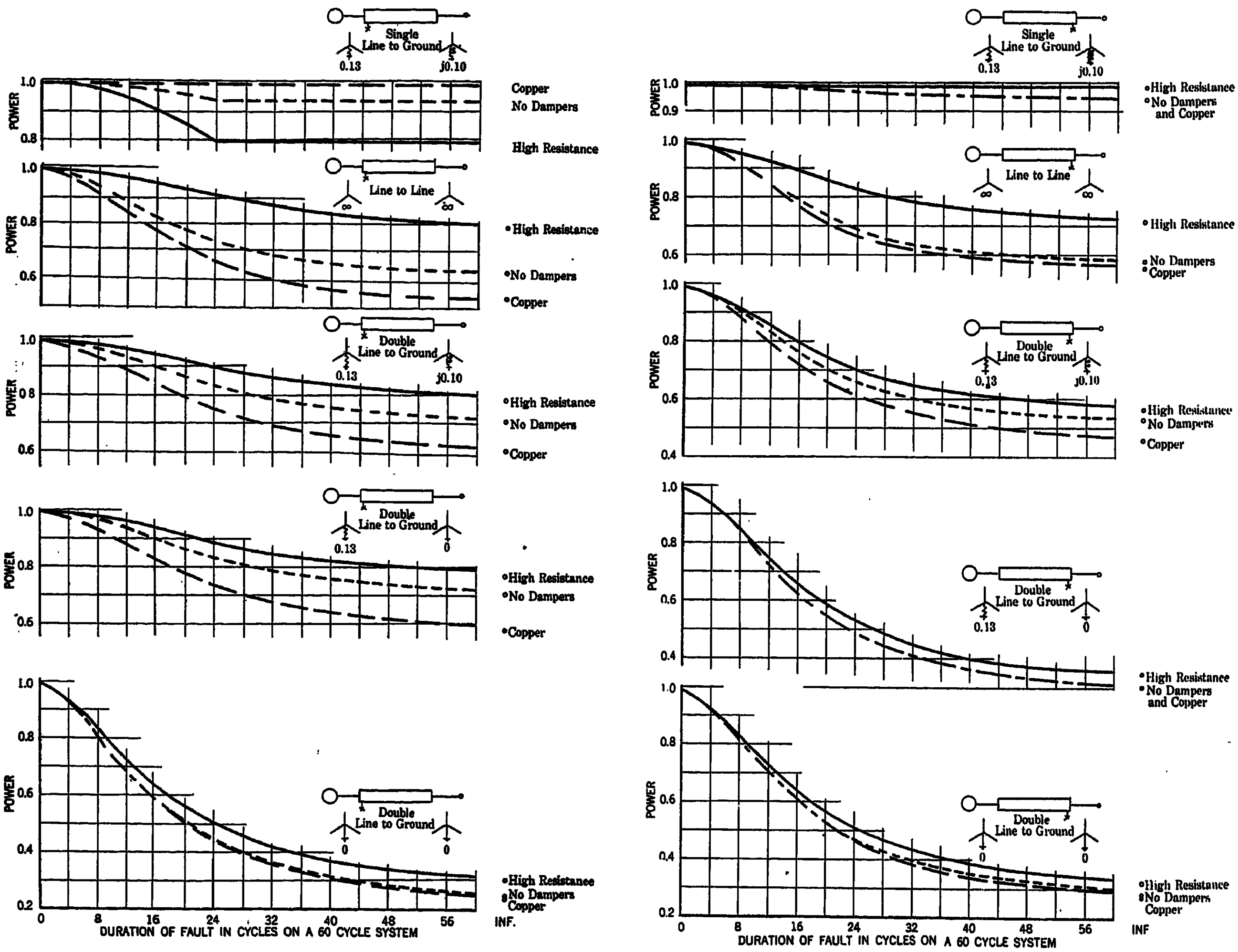

FIG. 3—STABILITY LIMITS WITH DIFFERENT KINDS OF FAULTS AND DAMPER WINDINGS AS A FUNCTION OF THE DURATION OF THE FAULT

A. Fault on high-voltage side of sending-end transformer B. Fault on high-voltage side of receiving-end transformer

The above values of impedance were obtained by the method described in the discussion of negative sequence resistance in Appendix II.

There remains yet to evaluate the effect of these different impedances upon the power limits. This will, of course, depend upon the particular kind of fault, the location and the duration of the fault under consideration. Fig. 3 shows the maximum power that can be

transmitted on the given system for different kinds of faults, including the effect of the subsequent switching of the faulted line. It will be observed that the high-resistance dampers give the highest limits for all cases except for the single line-to-ground fault at the generator end, and for most cases the difference is quite considerable. The improvement made possible with the high-resistance damper may be made more evident by expressing the limits as a per cent of the minimum limit.

The above values of negative sequence resistance do not represent the ultimate that may be obtained by increasing the resistance of the damper bars. Further increase is possible with some additional gain in stability limit. However, as the resistance is still further increased, the reactance also increases because, in the equivalent circuit[3] for the machine, the field winding parallels the damper circuit; and for very high resistance the reactance approaches that of a machine with no dampers. In addition, in the equivalent circuit for the system, for a line-to-line fault on the high-tension bus at the generator end, the negative-sequence impedance of the machine and transformer is paralleled by the negative-sequence impedance of the rest of the system. As the negative-sequence résistance of the machine increases more of the total negative-sequence current is diverted to the rest of the system. A point is finally reached at which the decrease in negative-sequence current through the machine more than compensates for the increase in resistance.

As the negative-sequence energy absorbed in the machine increases, heating of the damper windings may constitute a limitation. A terminal-to-terminal fault on the machine or a line-to-line fault on the high-tension bus will produce a temperature rise of about 80 deg. cent. per second for a machine with 0.12 per unit negative sequence resistance, assuming all the energy is absorbed thermally in the damper bars themselves and making no allowance for thermal conduction or radiation to the surrounding laminations. With even these assumptions, no dangerous temperatures should result if the fault held on for three to five seconds. For other types of faults, such as single or double faults to ground, the negative sequence current through the machine is smaller and consequently the heating is also much smaller.

The normal current unbalances met are of no consequence in determining dangerous operating temperatures. A 10 per cent negative sequence current which would result if the currents in the three phases are 1.15–1.0–1.0–or 1.0–1.1–1.2 produces but ¼ per cent loss in the dampers for the 0.12 per unit negative sequence resistance machine. Such a machine, of course, does not lend itself to single phase operation so readily as one with a copper damper.

Alteration in Generator Torque During and Following a System Fault due to Currents in the Damper Windings

At times of any symmetrical change in machine conditions such as, short circuits or change in operating angle, transients are set up in both the field and armature. For all practical purposes these transients may be reduced to (1) a unidirectional component in the field with its associated fundamental frequency transient in the armature, and (2) a fundamental frequency transient in the field and a unidirectional and double frequency transient in the armature. It can be shown that while the latter components are important in determining the maximum mechanical stress between turns or the maximum impulsive torque exerted on the shaft, for three-phase short circuits on the terminals of the machine, they are unimportant, because of their rapid decrement for other types of faults, in their net effect upon the angular oscillations following a system disturbance. The latter components will, therefore, be neglected and consideration given to the former. As previously stated, unbalanced faults can be reduced to equivalent symmetrical circuits, so that the analysis pertaining to transients in symmetrical circuits may be applied to the resultant positive sequence network.

The Blondel two-reaction method of analysis of salient pole machines, extended to include the effect of amortisseur torque will be used in this study. The nomenclature by Doherty and Nickle[4] in their excellent analysis of synchronous machines will be used as far as possible. Armature resistance will be neglected.

At times of change in load occasioned by sudden change in circuit condition or rotor oscillations, the flux linkages with the field winding (assuming no damper windings) tend to remain constant and since the present investigation has to do with damper windings, the exciter voltage shall be assumed to vary instantaneously in such manner as to make the assumption of constant flux linkages with the field winding rigorously true. This corresponds to the assumption of constant e_d', where e_d' is the "transient internal voltage in the direct axis." To obtain this voltage in terms of the terminal voltage and drops within the machine for a machine without damper windings (or a machine with damper windings for steady state conditions) it is necessary to use the transient reactance x_d' of the machine.

Because of the close proximity of the damper windings to the air gap, the damper windings tend to prevent any change in the air gap flux. The extent to which this fails to hold depends upon the leakage flux associated with the damper windings and is therefore affected by the nature of the magnetic circuit surrounding the individual bars. Buried damper bars surrounded by a complete iron circuit possess considerable leakage and would not be nearly as effective in maintaining the air gap flux as bars with an intervening air gap. This effect may be evaluated by the introduction of a new reactance x_d'', the subtransient reactance. Using this reactance instead of the synchronous reactance a new voltage, e_d'', which we shall term the "subtransient voltage in the direct axis" is obtained. It is the voltage associated with flux linkages with the damper windings in the di-

rect axis. In the event of any sudden change it is this quantity which remains constant.

The time constant of the transient due to the current in the damper winding is in general quite small so that after a very short time the flux in the air gap changes to that corresponding to zero current in the damper winding and constant flux linkages with the main field winding. For our present discussion this is the steady state condition because the original assumption premised such a variation in exciter voltage as to maintain constant flux linkages with the field winding. The steady state value which e_d'' tends to approach may then be obtained by determining i_d for e_d' constant, using for this purpose the corresponding constants of the machine, namely, x_q and x_d'. The steady state value of e_d'' is then

$$e_d''_{(steady\ state)} = e_d' - (x_d' - x_d'')\, i_d \qquad (2)$$

or substituting i_d from Eq. (17) in the appendix

$$e_d''_{(steady\ state)} = e_d' - (x_d' - x_d'')\,(K_3\, e_d' - K_4\, E \cos\theta) \qquad (3)$$

As in any problem involving a driving force, a variable, and a simple lag of the variable behind the driving force, the rate of change of e_d'' is

$$\frac{d\, e_d''}{d\, t} = -\frac{e_d'' - e_d''_{(steady\ state)}}{T_d''} \qquad (4)$$

so that given the instantaneous value of e_d'', the time constant of the damper winding in the direct axis, T_d'', and the value of e_d'' would attain if θ were maintained constant at its instantaneous value, the value of $\frac{d\, e_d''}{d\, t}$ is determined. It will be observed from the above formula and values of K_3 and K_4 from the appendix that since no constants for the quadrature axis are present, the phenomena in the direct axis is independent of the fluxes in the quadrature axis.

Just as the fictitious voltages e_d' and e_d'' were utilized to designate the generated voltages associated with certain flux relations in the direct axis, e_q'' will be used to designate the voltage corresponding to the flux linkages with the damper winding in the quadrature axis. The steady state value of this voltage is from the appendix

$$e_q''_{(steady\ state)} = -K_1\,(x_q - x_q'')\, E \sin\theta \qquad (5)$$

The voltage, e_q'', is approximately equal to the voltage produced by the quadrature flux. It is restrained from changing, instantly, by currents induced in the damper windings. The rate at which it changes is

$$\frac{d\, e_q''}{d\, t} = -\frac{e_q'' - e_q''_{(steady\ state)}}{T_q''} \qquad (6)$$

To evaluate the effect of these damper currents, a line-to-line fault was assumed applied for 0.2 second to the high-tension bus at the generating end of the 60-cycle system shown schematically in Fig. 4. The power-angle diagram for $e_d' = 1$ (assuming no damper currents) is shown for the three-circuit conditions involved—two lines in service, before the fault; the fault on the system; and the fault removed, one line in service. Then for an initial power of 0.8, the angle-time curve was obtained. The assumption was then made that the damper currents would not change the angle-time curve appreciably—an assumption that the results will be seen to justify. Then knowing the variation of the angle with time, $e_d''_{(steady\ state)}$ and $e_q''_{(steady\ state)}$ can also be determined, from which by a step-by-step process, using the time constants for a copper damper, the instantaneous values of e_d'' and e_q'' can be calculated. Converted into power the increment in power is shown by the shaded areas. It will be observed that during the fault condition the generator output decreases but following the clearing of the fault the output increases. The net result is quite small for, expressing the effect in terms of the actual increment in power limit, it amounts to slightly less than ½ per cent, which in view of the other effects of damper windings is negligible. Brass or higher resistivity material would be correspondingly smaller.

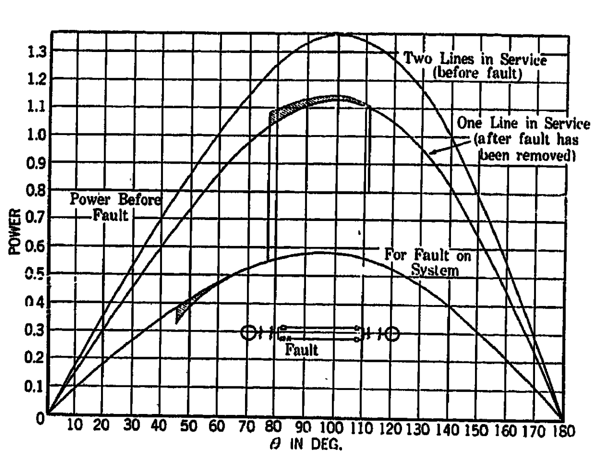

FIG. 4—INCREMENT IN POWER DURING AND FOLLOWING A FAULT DUE TO INDUCED CURRENTS IN THE DAMPER BARS FOR A TYPICAL MACHINE ASSUMING COPPER DAMPERS

Line reactance $= j\,0.3$ per line
Transformer reactance $= j\,0.1$
$x_d = 1.0$ $x_q = 0.6$
$x_d' = 0.4$ $x_q'' = 0.35$
$x_d'' = 0.3$
$T_{do} = 5.0$ $T_{do}'' = 0.04$ $T_{qo}'' = 0.12$
$e_d' = 1.0$ $E = 1.0$
Stored energy per kv-a. = 2.6 kw-sec.

HUNTING

The phenomena associated with hunting[7] may be visualized by assuming the rotor to oscillate about the mean operating angle θ. As the angle increases the demagnetizing component tends to increase and thus decrease the flux in the direct axis. However, due to the induced currents in the field and damper windings the flux and the internal voltages corresponding therewith lag behind the values which they finally would attain if the angle remained constant at any particular value. During the oscillation, therefore, instead of moving along the same locus with increasing and de-

creasing displacement, the instantaneous value of internal voltage forms a loop. The damper winding serves a similar function in the quadrature axis as the field and damper winding do in the direct axis, resulting in a similar voltage loop for the quadrature transient voltage. The voltage loops so formed can be readily transformed into a similar power loop, the area of which represents the energy absorbed per cycle of system oscillation. The results of such calculations are plotted in Fig. 5 which shows the energy absorbed per cycle of

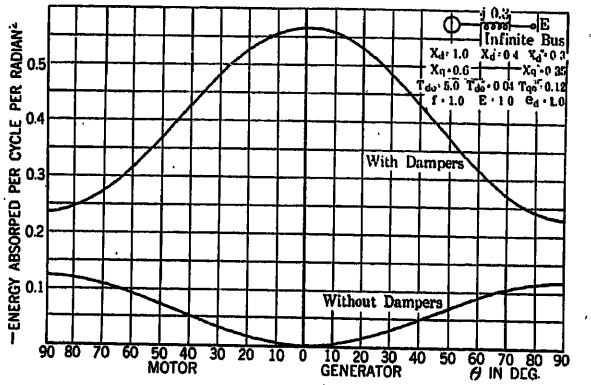

Fig. 5—Energy Absorbed per Cycle of System Oscillation for Small Oscillations for Typical Machine with and without Copper Damper Windings

system oscillation (per radian)² for small oscillations. The generators were assumed to be typical with and without copper dampers and tied to an infinite bus through a reactance of 0.3 per unit. Machines without damper windings can be influenced only by the variation in the demagnetizing component of current because the flux in the quadrature axis can change instantaneously. For small values of θ the demagnetizing current does not change appreciably for small variations in θ so that one may expect the energy absorbed to be small, but as θ increases the variations and hence the energy absorbed becomes greater. With damper windings, currents are induced in both the field and damper windings in the direct axis and in the damper windings alone in the quadrature axis.

The ordinates of these curves divided by the square of the amplitude of oscillation are a measure of the energy absorbed per cycle of oscillation, and represent the variation in energy input necessary to sustain oscillations of the given amplitude. For other variations in input the amplitude of the oscillations vary as the square root of the energy. To form a more concrete conception of the variations in power assume an operating angle of 30 deg., the machine equipped with copper dampers, and a sinusoidal oscillation of 10 deg. in amplitude. The power-angle diagram for the system under consideration and for which the curves in Fig. 5 were obtained is plotted in Fig. 6 along with the power loop which is shown dotted. The area of the power loop is $\pi \, \Delta \, P_m \, \Delta \, \theta_m$ in which $\Delta \, P_m$ is the maximum deviation of the actual locus from the power-angle curve for the mean operating angle. It may be seen that the energy per cycle per (radian)² for this particular case is 0.48, so that the energy per cycle for 10 deg. is 0.0146. Equating this to the above, $\Delta \, P_m = 0.0267$.

These data in themselves are not sufficient to form a conclusion as to the desirability of installing damper windings for the purpose of suppressing hunting, but merely show that cyclic variations in torque, from the mean, of the order of 2.5 per cent may arise in the prime mover and be absorbed in the generator for an angular oscillation of 10 electrical degrees and a frequency equal to unity. To complete the story it is necessary to know whether such torques are usually present. It is known that the torque characteristics of hydraulic and steam turbines are very uniform and that alternators driven by such prime movers do not usually experience hunting troubles. Improper governor adjustment may, however, give rise to such phenomena. In such a case, the cause should be sought at the source of the trouble rather than in the dampers.

The curves of energy absorbed are also of assistance in estimating the decrement of oscillations following a disturbance. Assume that the operating angle following a certain disturbance is 30 deg. (see Fig. 6) and that at some instant the peak of the oscillation has been reached at the point A at 40 deg. The relative velocity at this instant is zero. A measure of the stored energy of oscillation at this instant is the area of the shaded

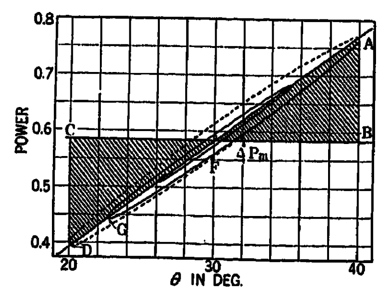

Fig. 6—Illustrating Maximum Deviation of Power from Mean for Sinusoidal Oscillations and Decrement of Free Oscillations Due to Energy Absorbed

portion bounded by $O\,A\,B$, which is $\frac{1}{2} \times 0.187 \times \frac{10 \times \pi}{180} = 0.0163$. If there were no lag of internal flux behind the steady state value, the locus of the operating point coincides with the line $O\,A\,D$, and the angle decreases until the area $O\,C\,B$ equals the area $O\,A\,B$, but actually by the time the point of maximum negative oscillation is reached the energy of a half-cycle oscillation, namely $\frac{1}{2} \times (0.0146) = 0.0073$, has been absorbed. The remaining energy which is again all in the form of potential energy is $0.0163 - 0.0073 = 0.0090$ and the amplitude of oscillation $10\sqrt{\frac{0.0090}{0.0146}} = 7.42$ degrees. The amplitude of subsequent successive half cycles bear the same relation to each other,

producing the locus shown, resulting in a time constant for the decrement of the oscillation of 1.7 seconds. It should be recognized that this is not strictly correct as the damping was assumed to be proportional to the area of the dotted loop whereas in reality it should be proportional to the somewhat smaller loop. As the operating angle increases the decrement decreases until at around 90 deg. it is but half of the value at 30 deg. (see Fig. 5). For a machine with brass dampers operating under the same conditions the time constant is 10 seconds. With brass, therefore, the duration of the oscillation would be six times as long.

The property of high damping is of no particular value for such simple systems that can be reduced to an equivalent generator and motor tied together through a transmission line. It only means that the oscillations do not continue so long. However, in more complicated systems involving compound oscillations following system disturbances, it is possible that pull-out of an individual unit will not take place until after several oscillations of the fundamental oscillation, in which case the damping afforded by the copper damper should be of considerable value. This phenomena must not be confused with the oscillations that accompany improper governor adjustments.

Breaker Duty and Quick Response Excitation

A copper damper winding will increase the breaker duty from the standpoint of increased current but will reduce the duty from the standpoint of lower recovery voltage, the function of the damper being to retard the change in air gap flux. While the effect upon the voltage is more important neither effect is sufficiently pronounced to influence the choice of the desirable damper. Similar effects are present with a high resistance damper except that the lag of the recovery is much smaller. Another effect enters with high-resistance dampers. Because of the large energy component of current the relative phase position of current and voltage shifts so that the voltage is no longer at its maximum as the current passes through zero and interrupts the circuit, thus reducing the recovery voltage. It may be argued that this condition does not hold for a three-phase fault but in opening the three-phase fault the breaker must pass through the phase-to-phase condition. On the whole these effects are too small to consider in applying a breaker.

The question also arises as to the effect of the damper winding on quick response excitation systems. The amount of copper associated with the damper winding is always small in comparison with that associated with the main winding and for that reason is relatively unimportant in connection with quick response. The actual tendency, of course, is to hinder any change of flux linked with the damper winding so that when the function of quick response system is to just maintain the flux, the dampers are an aid but, when the function of excitation is to actually increase the flux, the dampers are a hindrance. These effects become less important as the damper resistance increases.

Double Deck and Other Special Types of Damper Windings

In reviewing the properties of the different kinds of dampers, it will be recalled that from the standpoint of power limits as affected by the negative sequence impedance the order of preference is high-resistance damper, no damper and copper damper. It was also shown that the induced currents due to changes in the positive sequence current were practically negligible, even for the copper damper, in their effect upon stability limits. However, copper dampers are much more effective in damping the oscillations following an oscillation and for this reason may be effective in raising the stability limit in more complicated interconnections in which pull-out occurs some time after the first peak of the oscillation due to the presence of a compound oscillation.

Several types of special damper windings have been suggested which have for their object the combination

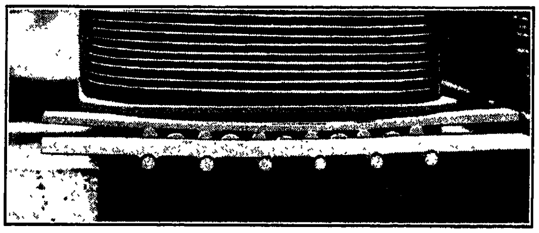

Fig. 7—Double-Deck Damper Construction

of the advantages of the high-resistance damper from the standpoint of negative sequence loss and the copper damper from the standpoint of damping action. These dampers sought to take advantage of the fact that the rotor currents determining the negative sequence are of double system frequency whereas the currents determining the damping action proper are of the frequency of the electro-mechanical oscillations of the system. In effect a damper was sought having a large skin effect ratio at double system frequency. What appears to be the most promising of this type of damper is shown in Fig. 7 which consists essentially of two distinct sets of windings, the lower one of copper, completely buried in the rotor iron, and the upper one of high-resistance material with an air gap inserted in its magnetic circuit. At double system frequency the reactance of the buried bars is so great that most of the current will circulate in the upper high-resistance bars producing a high-negative sequence resistance. At the low frequencies encountered in system oscillations, (about 1 to 1.5 cycles per second) the reactive drop is very small, so that the resistance is controlling in determining the current distribution between bars. In this case most of the current passes through the low-resistance copper, the presence of high-resistance bars thus detracting little from the effectiveness of the copper bars.

The extent to which these conditions hold is dependent upon the saturation of the iron surrounding the copper bars. Tests have been made on different proportions of iron circuit, a typical result of which is shown in Fig. 8. The ratio of currents in the high resistance and copper bars was determined for 0, 17.8, 25, 39, and 60 cycles, for currents ranging from 600 to 2,000 amperes, the latter being the order of magnitude expected for line-to-line faults on the high-tension bus. The results so obtained were extrapolated to 120 cycles and 3,000 amperes by plotting on logarithmic paper, resulting in the curves shown. The curve for 120 cycles shows how saturation affects the current distribution between bars. However, it is not until about 1,000 amperes is reached that saturation affects the loss importantly. A ratio of three-to-one in currents decreases the loss to about 90 and 50 per cent, respectively, of the value it would have were the copper bars not present. These tests, therefore indicate, that the double winding does not impair the characteristics that the low-resistance winding possessed acting alone, but does, especially at high currents, somewhat impair the characteristics of the high-resistance winding.

Structurally a double damper of this character offers some difficulty. Since practically all of the energy is absorbed by the heat capacity of the high-resistance bars, the rise in temperature of these bars is much greater than that of the copper bars. The difference in expansion of the hot and cold bars requires that the ends of the two sets of bars be not fastened together.

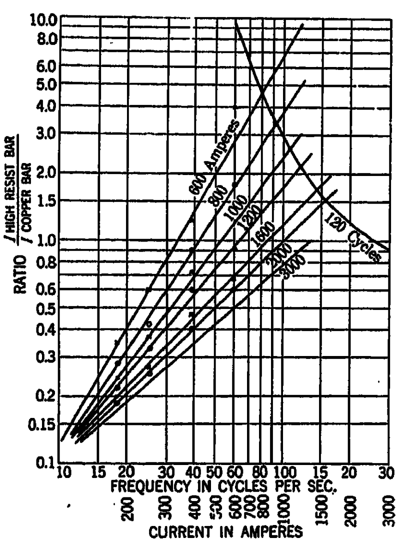

Fig. 8—Showing Ratio of Current Distribution Between High Resistance and Copper Bars as a Function of Frequency and Current

One solution of this difficulty is the use of two separate end rings. In tests made on a synchronous condenser it was found that insulating the end rings from the bar connectors had little effect upon the negative sequence resistance. Taking advantage of this fact the high-resistance bars may be welded to a connector laid flat against the side of the pole piece instead of in the conventional manner, the connections between poles being omitted.

Conclusions

The choice of the most appropriate damper winding is dependent upon the emphasis to be placed upon the different characteristics. The desirable property of rapid damping, associated with copper dampers, should

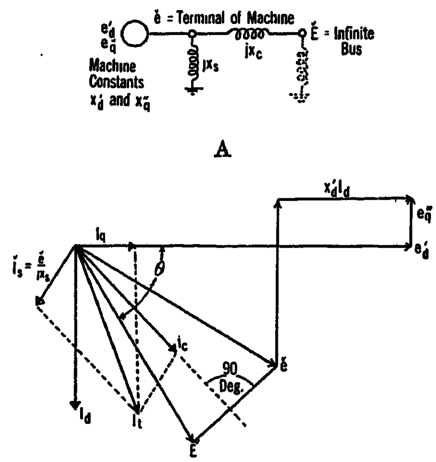

Fig. 9—Vector Diagram for Synchronous Machine with Series and Shunt Loading

be of value only in special cases in which there is danger of compound oscillations of such character that pull-out occurs on the second or third oscillation. Only rarely has such a case come to the attention of the author and his associates. When pull-out does take place it usually occurs on the first swing or not at all. High-resistance dampers should be of value regardless of the nature of the oscillations and from this viewpoint are more desirable. Double-deck or similar dampers are somewhat of a compromise, conferring to the machine some damping characteristics (but not as much as though both windings were of copper) and at the same time increasing the stability limit because of the increase in power absorbed by the damper (but not as much as for a higher resistivity material occupying the same space and using the same temperature; a loss must result either in stability limit or in temperature tolerance). These conclusions are premised upon a given pole shoe. Of course, more effective dampers can always be installed if more space be made available, by increasing the distance from field coil to the outer edge of the pole shoe. This necessarily increases the diameter of machine and results in a greater increase in cost than is justifiable by the improvement in stability.

Appendix I

Effect of Damper Currents During and Following Faults

Symmetrical or unsymmetrical faults on simple two-machine systems can always be reduced to an equivalent circuit of the form shown in Fig. 9A in which

x_s is a shunt reactance across the terminals of the machine and x_c a series reactance. Assuming an infinite bus at the receiving end of voltage E, the shunt admittance, shown dotted, will not enter the problem. The power output of the machine in terms of the internal voltages in the two axes e_d' and e_q'' and the corresponding reactances x_d' and x_q'' may be obtained as follows.

Referring to Fig. 9B

$$i_q - j\, i_d = \check{i}_s + \check{i}_c = \frac{\check{e}}{j\, x_s} + \frac{\check{e} - \check{E}}{j\, x_c}$$

$$= \left(\frac{1}{j\, x_s} + \frac{1}{j\, x_c} \right) \check{e} - \frac{\check{E}}{j\, x_c} \qquad (7)$$

But

$$\check{e} = e_d' - x_d'\, i_d + j\,(-\, x_q''\, i_q + e_q'') \qquad (8)$$

$$\check{E} = E \cos \theta - j\, E \sin \theta \qquad (9)$$

Substituting e and $\check{E}$

$$i_q - j\, i_d = -\, j\, \frac{x_s + x_c}{x_s\, x_c}\, e_d' + j\, \frac{(x_s + x_c)\, x_d'}{x_s\, x_c}\, i_d$$

$$- \frac{(x_s + x_c)}{x_s\, x_c}\, x_q''\, i_q + \frac{(x_s + x_c)}{x_s\, x_c}\, e_q'' + j \frac{E}{x_c} \cos \theta + \frac{E}{x_c} \sin \theta$$

Equating reals and imaginaries

$$i_q \left[1 + \frac{(x_s + x_c)\, x_q''}{x_s\, x_c} \right] = \frac{E}{x_c} \sin \theta + \left(\frac{x_s + x_c}{x_s\, x_c} \right) e_q''$$

or

$$i_q = \frac{x_s}{x_s\, x_c + x_s\, x_q'' + x_c\, x_q''}\, E \sin \theta$$

$$+ \frac{(x_s + x_c)}{x_s\, x_c + x_s\, x_q'' + x_c\, x_q''}\, e_q'' \qquad (10)$$

and

$$i_d \left[1 + \frac{(x_s + x_c)\, x_d'}{x_s\, x_c} \right] = \frac{x_s + x_c}{x_s\, x_c}\, e_d' - \frac{E}{x_c} \cos \theta$$

or

$$i_d = \frac{x_s + x_c}{x_s\, x_c + x_c\, x_d' + x_d'\, x_s}\, e_d'$$

$$- \frac{x_s}{x_s\, x_c + x_c\, x_d' + x_d'\, x_s}\, E \cos \theta \qquad (11)$$

Letting

$$K_1 = \frac{x_s}{x_s\, x_c + x_c\, x_q'' + x_q''\, x_s} \qquad (12)$$

$$K_2 = \frac{x_s + x_c}{x_s\, x_c + x_c\, x_q'' + x_q''\, x_s} \qquad (13)$$

$$K_3 = \frac{x_s + x_c}{x_s\, x_c + x_c\, x_d' + x_d'\, x_s} \qquad (14)$$

$$K_4 = \frac{x_s}{x_s\, x_c + x_c\, x_d' + x_d'\, x_s} \qquad (15)$$

then

$$i_q = K_1\, E \sin \theta + K_2\, e_q'' \qquad (16)$$

$$i_d = K_3\, e_d' - K_4\, E \cos \theta \qquad (17)$$

Power Output of Machine $= P$

$$P = (e_d' - x_d'\, i_d)\, i_q + (-\, e_q'' + x_q''\, i_q)\, i_d$$

$$= e_d'\, i_q - e_q''\, i_d + (x_q'' - x_d')\, i_d\, i_q$$

Substituting values of i_d and i_q

$$P = K_1\, e_d'\, E \sin \theta + K_2\, e_d'\, e_q'' + K_3\, e_q''\, e_d' + K_4\, e_q''\, E \cos \theta$$

$$+ (x_q'' - x_d') K_1 K_3 E\, e_d' \sin \theta - (x_q'' - x_d') K_2 K_4 E\, e_q'' \cos \theta$$

$$+ (x_q'' - x_d') K_2 K_3\, e_q''\, e_d' - (x_q'' - x_d') K_1 K_4 E^2 \sin \theta \cos \theta$$

$$= [-\, K_3\, e_d' + K_2\, e_d' + (x_q'' - x_d')\, K_2 K_3\, e_d']\, e_q''$$

$$+ [K_1\, e_d'\, E + (x_q'' - x_d')\, K_1 K_3 E\, e_d'] \sin \theta$$

$$- [(x_q'' - x_d')\, K_2 K_4 E - K_4 E]\, e_q'' \cos \theta$$

Substituting the values of K_2 and K_3 in the coefficient

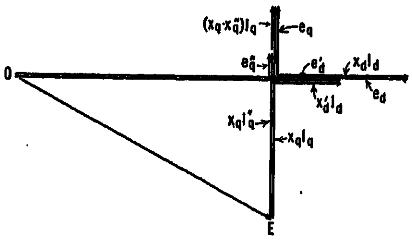

FIG. 10—VECTOR DIAGRAM FOR SYNCHRONOUS MACHINE SHOWING RELATION BETWEEN TRANSIENT AND SUBTRANSIENT REACTANCES

of e_q'', it will be seen to reduce to zero, and there results

$$P = [1 + (x_q'' - x_d')\, K_3]\, K_1 E\, e_d' \sin \theta$$

$$+ [1 - (x_q'' - x_d')\, K_2]\, K_4 E\, e_q'' \cos \theta$$

$$- \left[\frac{(x_q'' - x_d')\, K_1 K_4}{2} \right] E^2 \sin 2\, \theta \qquad (18)$$

When the power expression is used in terms of e_d'', x_d'' must be substituted for x_d' in both the power expression and the evaluation of K_3 and K_4.

DETERMINATION OF $e_q''_{(steady\ state)}$ AND $\frac{d\, e_q''}{d\, t}$

The steady state value of i_q may be obtained for any given angle by using the above developed formula for i_q and letting e_q'' therein be equal to zero and $x_q'' = x_q$, therefore

$$i_q = \frac{x_s}{x_s\, x_c + x_c\, x_q + x_q\, x_s}\, E \sin \theta \qquad (19)$$

For steady state conditions, from Fig. 10

$$e_q - e_q'' = (x_q - x_q'')\, i_q$$

and since $e_q = 0$, then

$$e_{q\ (steady\ state)}'' = -(x_q - x_q'')\, i_q = \frac{-\,(x_q - x_q'')\, x_s}{x_s\, x_c + x_c\, x_q + x_q\, x_s}\, E \sin \theta \qquad (20)$$

Substituting $e_q''_{(steady\ state)}$ in Equation (6)

$$\frac{d\, e_q''}{d\, t} = \frac{\dfrac{(x_q - x_q'')\, x_s}{x_s\, x_c + x_c\, x_q + x_q\, x_s} E \sin \theta - e_q''}{T_q''} \tag{21}$$

Substituting $e_q''_{(steady\ state)}$ in Equation (6)

$$\frac{d\, e_q''}{d\, t} = \frac{1}{T_q''} \left[\frac{(x_q - x_q'')\, x_s}{x_s\, x_c + x_c\, x_q + x_q\, x_s} E \sin \theta - e_q'' \right] \tag{22}$$

Appendix II

Negative Sequence Resistance

The nature of the negative sequence resistance is best visualized by analyzing the phenomena occurring in induction motors. Fig. 11 shows the usual equivalent circuit* of an induction motor in which

r_s = Stator resistance
x_s = Stator leakage reactance at rated frequency.
r_r = Rotor resistance.
x_r = Rotor leakage reactance at rated frequency.
Z_m = Shunt impedance to include the effect of magnetizing current and no load losses.
E_s = Applied voltage.
I_s = Stator current.
I_r = Rotor current.
s = Slip.

All of the above quantities are assumed to be given in per unit quantities.

The justification for this diagram may be seen briefly

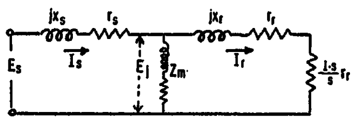

Fig. 11—Equivalent Circuit of Induction Motor

as follows: The air gap flux due to the currents I_s and I_r induce the voltage E_i in the stator and $s\, E_i$ in the rotor. In the rotor the impedance drop is

$$r_r\, I_r + j\, s\, x_r\, I_r$$

since the reactance varies with the frequency of the currents in the rotor. The rotor current is therefore determined by the equation:

$$s\, E_i = r_r\, I_r + j\, s\, x_r\, I_r$$

or

$$E_i = \frac{r_r}{s} I_r + j\, x_r\, I_r \tag{23}$$

It follows from this equation that the rotor circuit can be completely represented by placing a circuit of impedance $\frac{r_r}{s} + j\, x_r$ across the voltage E_i. The total power absorbed by $\frac{r_r}{s}$ must be the sum of the rotor losses and the useful shaft power, so that, resolving $\frac{r_r}{s}$ into the resistances r_r and $\frac{1-s}{s}\, r_r$ the power absorbed by r_r represents the rotor copper loss and the power absorbed by $\frac{1-s}{s}\, r_r$ represents the useful shaft power.

Neglecting r_s and the real part of Z_m, the only real power is that concerned in the rotor circuit.

Now assume that the induction motor is loaded by means of a d-c. generator connected to the shaft. At small slips the electrical input into the stator is equal to the copper loss, that is, the $I_r^2\, r_r$ of the rotor, plus the shaft load. With the rotor locked the shaft load is zero and the total electrical input into the stator is equal to the rotor copper loss. At 200 per cent slip, *i. e.*, with the rotor rotating at synchronous speed in the reverse direction, the copper loss is $I_r^2\, r_r$, the electrical input into the stator is $\frac{I_r^2\, r_r}{2}$ and the shaft load $\frac{1-2}{2}\, r_r\, I_r^2$ or $-\frac{I_r^2\, r_r}{2}$. A negative shaft load signifies that the d-c. machine instead of functioning as a generator is now a motor. Physically that is just what would be expected, for, as the slip increases from zero the shaft power increases to a maximum and then decreases to zero for 100 per cent slip. A further increase in slip necessitates motion in the opposite direction, which requires a driving torque. It will be observed, therefore, that at 200 per cent slip, the electrical input into the stator is equal to the mechanical input through the shaft, half of the copper loss is supplied from the stator and half through the shaft. This is the condition obtaining with respect to the negative sequence in which the rotor is rotating at a slip of 200 per cent relative to the synchronously rotating negative sequence field in the stator. Half of the machine loss associated with the negative sequence current is supplied from the stator and half by shaft torque through the rotor.

The factor of fundamental importance is the power supplied by the stator and through the shaft, which can always be determined by solving the equivalent circuit involving the stator and rotor constants and the magnetizing current constants. A more convenient device, since s is constant and equal to 2 for the negative sequence, is to reduce the equivalent network to a simple series impedance as shown in Fig. 12. The components of this impedance will be called the negative sequence resistance R_2 and negative sequence reactance X_2. The values of these constants are also

*For more detailed description of this circuit see any standard text book such as Ralph R. Lawrence's, "Principles of Alternating Current Machinery."

given in Fig. 12. The current flowing through the negative sequence impedance is the current flowing through the stator of the machine and the power loss in R_2 is equal to the loss supplied from the stator of the machine and the loss supplied through the rotor.

The total electrical effect of the negative sequence resistance is obtained by inserting the negative sequence resistance in the negative sequence network for the system in the usual manner and solving the network in

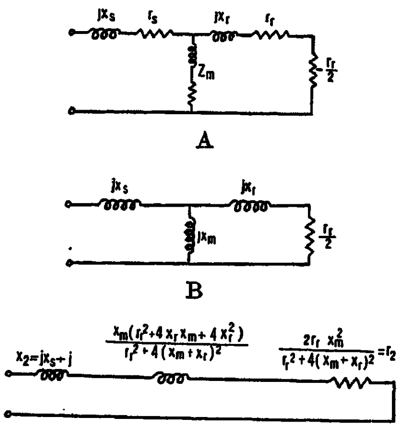

FIG. 12—DEVELOPMENT OF NEGATIVE SEQUENCE RESISTANCE AND REACTANCE FROM EQUIVALENT CIRCUIT OF INDUCTION MOTOR

a. Negative sequence diagram for induction motor
b. Neglecting armature and no load losses
c. Simplified network—negative sequence resistance and reactance

the usual manner. All three of the sequence currents are thus affected by a change in the negative sequence resistance. The total electrical output of a generator is equal to the total terminal power output plus the losses in the machine. However, since the negative and zero sequence power outputs are merely the negative of their losses the contribution to the electrical output by the negative and zero sequences is zero. The total electrical output is therefore that due to the positive sequence and to include the positive sequence armature resistance loss it is only necessary to use the positive sequence internal voltage in the calculations. Or viewed differently, since there are no internal generated voltages of the negative and zero sequence, the corresponding internal power must be zero. In addition to this electrical output which produces a torque tending to decelerate the rotor, there also exists the negative sequence shaft power supplied through rotor. It was shown that the value of this power tending to decelerate the rotor is numerically equal to the negative sequence power supplied to the stator which is equal to the loss absorbed by the negative sequence resistance. Therefore, the total decelerating power is equal to the positive sequence power output plus the loss in the negative sequence resistance.

The assumption was made that the stator resistance and the losses in magnetizing branch were neglected. The justification for this assumption lies in the fact that they are usually small so that their effect on the net result is unimportant and in addition, in the comparative analysis under consideration, the difference will be completely submerged. For greater refinements, the stator resistance and the losses in the magnetizing branch can be taken into consideration by substituting them in the equivalent circuit and reducing that circuit to a simple series resistance and reactance, wherein the resistance becomes the negative sequence resistance and the reactance the negative sequence reactance. The ratio of the negative sequence shaft power to the negative sequence stator power is then equal to the ratio of the power loss in $\frac{r_r}{2}$ for unit negative sequence current in the stator to r_2. This ratio can be obtained very easily by test by measuring the shaft torque and the negative sequence input when negative sequence voltages only are applied to the stator.

While this analysis has premised induction motor construction, the conclusions may also be applied to multicircuit rotors.

The significance of these considerations may be illustrated by a description of the method utilized to determine the negative sequence resistance. For this purpose two terminals of the machine under test were short-circuited and the machine driven at rated frequency by means of a d-c. motor. The equivalent circuit and vector diagram for this connection are shown in Fig. 13.

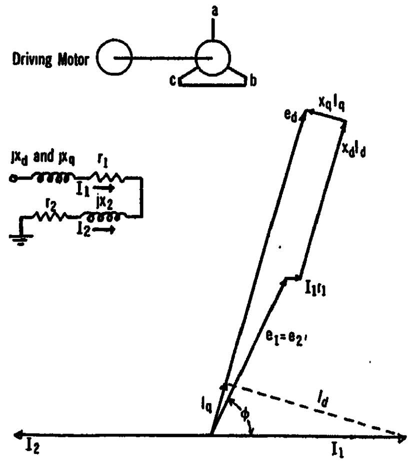

FIG. 13—NEGATIVE SEQUENCE RESISTANCE OF SYNCHRONOUS MACHINES

The positive sequence reactions are resolved into the two axes—the direct and quadrature. The positive sequence power at the terminals is equal to the product of e_1 and I_1 and the cosine of the angle ϕ. It will be observed that this power is positive. However, the negative sequence power output is equal to e_2, I_2 and the cosine of the angle between e_2 and I_2, and since $I_2 = -I_1$, and $e_1 = e_2$, the negative sequence power output is the negative of the positive sequence power output, which, of course, must follow since the output of ma-

chine is zero. A negative output is equivalent to a positive input. This input is equal to $r_2 I_2^2$. Therefore, the positive sequence terminal output is $r_2 I_2^2$ and the total shaft load due to the positive sequence is equal to $r_2 I_2^2 + r_1 I_1^2$. It has been shown that the negative sequence shaft load (neglecting the armature resistance) is equal to the negative sequence input or $r_2 I_2^2$. Including the armature resistance but still neglecting the loss in the magnetizing branch and harmonics the negative sequence shaft load, since $I_2 = I_1$, is $(r_2 - r_1) I_2^2$. Therefore, the total tool input into the a-c. machine is equal to $r_2 I_2^2 + r_1 I_1^2 + (r_2 - r_1) I_2^2$ or $2 r_2 I_2^2$ and

$$r_2 = \frac{\text{Tool input}}{2 I_2^2} \tag{24}$$

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Discussion

W. F. Skeats: The author has pointed out that a damper winding has the effect of increasing the breaker duty from the point of view of increased current, but of decreasing the duty from the point of view of recovery voltage. I am in agreement with these statements.

It may be added that a high-resistance damper increases the current less and, if the breaker operates in about one-tenth of a second, decreases the recovery voltage more than does the low-resistance damper.

However, an additional and more pronounced effect upon breaker operation is found in the case of three-phase short circuits. Here the current is limited by the direct-axis subtransient reactance of the machine, whereas the recovery voltage of the first phase to clear is determined by the quadrature-axis subtransient reactance. This is because at the time of clearing, the phase clearing first links the quadrature axis of the machine. As a result, the recovery voltage of the phase clearing first suffers a factor equal to the ratio of quadrature to direct subtransient reactance, which may be as high as 2.5, on machines without amortisseur windings, and is only 1.1 or 1.2 on machines with amortisseur windings.

That this effect is important is strikingly demonstrated by a series of tests made on the system of the Northern States Power Company in September, 1925. The same plain-break oil circuit breaker was tested with power supplied from the Riverside steam station through step-up and step-down transformers and a 43-mile, 110-kv. transmission line and with power supplied directly from three water-wheel generators at Wissota. The results of these tests are shown in Table I. It will be noted that in spite of the slightly lower voltage at Wissota, the duty, as measured by breaker distress, was several times as great. Undoubtedly the existence of the long transmission line between the generator and the short-circuit point was partly responsible for the difference in breaker performance, but it is my opinion that the use of water-wheel-driven generators also had a decided influence.

This effect appears in three-phase short circuits and in two-phase-to-ground short circuits with very low zero phase sequence reactance. While these are not the most common types of short circuit, they are likely to be the most severe, and are therefore of importance.

This phenomenon will be influenced only to a very slight extent by the resistance of the amortisseur winding.

TABLE I

Source of power	Riverside	Wissota
Number of tests made	2	5
R. m. s. line-to-line volts before short circuit	15,000	13,200
Average initial r. m. s. current in the arc	1,400	1,420
Inches of arc	1.2	4.8
Half cycles of arc	3.5	10.0
Maximum pressure, lb./sq. in.	6.5	36.0

P. L. Alger: This paper presents a most interesting analysis of the stabilizing effects of amortisseur windings, which brings out very clearly the advantages of high-resistance amortisseur windings under prolonged fault conditions. Our studies of this subject have led us to conclusions in general accord with Mr. Wagner's, though more favorable to low-resistance amortisseurs

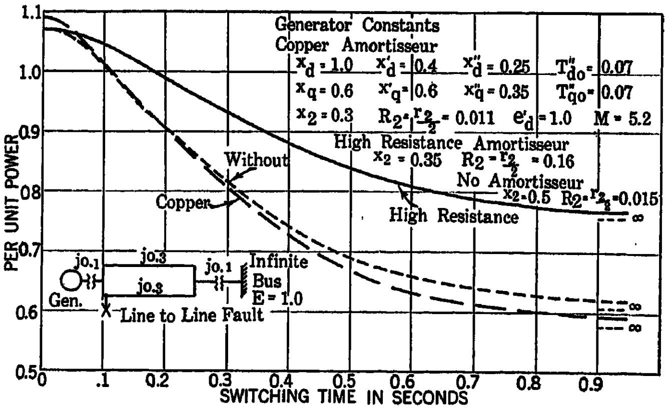

FIG. 1—POWER THAT CAN BE CARRIED THROUGH THE FIRST SWING WITH A LINE-TO-LINE FAULT BY A WATER-WHEEL GENERATOR WITH AND WITHOUT AMORTISSEUR WINDINGS

than his. The accompanying figure gives our results comparable with those for a line-to-line fault given in Fig. 3A of the paper. They assume the most favorable design of amortisseur in each case, and also assume infinite inertia at the receiving end.

An amortisseur winding produces three principal effects on stability, due respectively to its damping and braking torques, and to the increased fault current, resulting from the reduced negative phase sequence reactance.

The damping torque opposes all speed oscillations, and so is always beneficial. To secure an increased stability limit by this means, it is essential to make the damping torque large, while the generator is swinging from its full load angle toward the pull out angle, or in the neighborhood of 90 deg. displacement. This can be secured by putting maximum copper in the direct axis of the amortisseur. The amortisseur winding whose damping torque angle curve is shown in Fig. 5 of the paper has three times as much resistance in the direct axis as in the quadrature axis ($T_{oq}'' = 3\, T_{od}''$), and it is, therefore, not very effective, as indicated by its relatively low damping at the important 90 deg. point.

By thus designing a low-resistance amortisseur for maximum conductivity in the direct axis, an appreciable gain in stability limit can be secured from damping. If the fault was cleared instantaneously, this would be the only effect of the amortisseur, and so the initial point on the power time curve of the copper amortisseur is the highest of all, as shown in the figure. Besides the direct stability gain shown, a low-resistance amortisseur is beneficial during all system disturbances, in synchronizing, in damping out oscillations due to high-line resistance or faulty regulator action, and in holding machines in the same station together.

The increased fault current resulting from the reduced negative phase sequence reactance lowers the sending end voltage, and hence the power transferred, during the period the fault is on.

This effect can be minimized by designing the amortisseur with open end rings between poles, thus increasing the quadrature axis subtransient reactance without materially affecting the useful damping torque.

Also, if an unsymmetrical fault stays on an appreciable time, the negative phase sequence currents induced in the amortisseur produce resistance losses, and consequent braking torques on both generating and receiving end machines. Usually, the braking torque on the generator is about $^2/_3$ of the whole, so that with a high receiving end inertia compared to the generator inertia, the receiving end is not slowed down appreciably. However, the assumption of infinite receiving end inertia gives the maximum possible gain for the braking torque, and the actual gains in practise will be much less than those shown, if the receiving end inertia is not large.

By designing the amortisseur for maximum negative phase sequence resistance, a large gain in stability limit can thus be secured, for prolonged switching times. As the figure indicates, the braking torque of the high-resistance and the damping torque of the low-resistance amortisseur give equal benefits at about 0.05 seconds switching time, the high-resistance amortisseur being better for longer times.

I believe that the use of a low-resistance amortisseur is generally desirable, on account of its favorable damping action during all system disturbances, though its over-all effect on the stability limit is small. The use of a high-resistance amortisseur may be justified occasionally, but the actual gain in stability obtainable is small, if high-speed switching is used, while a risk of overheating on unbalanced loads is incurred. Either type gives an important reduction in recovery voltage on clearing a fault, and hence a reduction in switch duty.

C. F. Wagner: Mr. Skeats discusses the effect of damper windings upon recovery voltage having in mind in particular the comparison of high- and low-resistance dampers. His statements point to the conclusion that the difference in recovery voltage as influenced by the resistance of the damper winding is negligibly small. The case which shows up the low-resistance damper winding to best advantage in this regard is the three-phase short circuit but even in this case the effect of the damper winding resistance is negligibly small. As evidence of this fact we might refer to the criterion of recovery voltage suggested in Messrs. Park and Skeats' paper in which it was stated that the recovery voltage is dependent upon the value of x_q''. For the high-resistance damper discussed in my paper this value is not much different from that of the low-resistance damper winding. It follows therefore that for the range of damper winding resistance under consideration the resistance has little effect upon the recovery voltage.

Mr. Alger questions the choice of the direct axis time constant arguing that since $T_{qo}'' = 3\ T_{od}''$ the distribution of damper copper must be such that there is three times the copper effective in the quadrature axis as in the direct axis. Time constants, however, are not only dependent upon resistance but also upon inductance which accounts for the difference. Subsequent to the presentation of the paper I recalculated the effect of the induced currents in the damper bars for the larger values of time constants.

Results of these calculations for fault conditions again show that the unidirectional induced currents in the field winding, even with copper dampers, are extremely small in influencing the stability limits for the reasons elucidated in the paper. For high-resistance damper windings this effect is altogether negligible.

This discussion of effects of the order of one or two per cent calls for a review of the original assumptions. It will be recalled that the double frequency and the d-c. transient components of current in the armature were neglected. The former is always extremely small in its effect upon the power limits but the latter under certain cases may well reach values of the order of several per cent. The d-c. transient in the armature produces a stationary field which produces currents of system frequency in the damper windings. This phenomenon is very similar to that produced by the negative sequence currents in the armature except that the negative sequence currents produce currents of double frequency in the damper windings. The loss associated with the d-c. component of armature current is therefore proportional to the negative sequence resistance and is much greater with high-resistance damper windings than with low-resistance damper windings.

Including the effect of the d-c. transient in the armature as well as the d-c. transient in the damper windings, the detailed calculations show that the power limit curve plotted as a function of the time of fault duration is always higher for the high-resistance damper winding than for the low-resistance damper winding. Mr. Alger's argument that the two curves cross at 0.05-second switching time is therefore fallacious. I do not wish to emphasize by this discussion the importance of these small differences except to point out that, whereas Mr. Alger accredits their small beneficial effect to the copper dampers, their net effect when the d-c. component in the armature is considered is in favor of the high-resistance damper. These results were obtained by assuming an even larger value of T_{od}'' than suggested by Mr. Alger.

Mr. Alger also suggests designing the damper winding with open end rings between poles in an effort to minimize the negative sequence current. My associates and I have given this some consideration. Tests were made on the 5,000-kv-a. condenser previously referred to with the end rings insulated. Whereas z_q'' with the high-resistance damper and with the end ring connected was 0.37, with the end ring insulated z_q'' was 0.50. These values compare with z_q'' without dampers of 1.06. It is true that the open end ring produces a somewhat higher value negative sequence impedance but it can only do so by increasing z_q''. Using the argument of Mr. Alger's associates, Mr. Park and Mr. Skeats, a high value of z_q'' results in a higher recovery voltage on opening the circuit and increases the duty on circuit breakers.

To recapitulate, the larger values of time constants T_{do}'' and T_{qo}'' suggested by Mr. Alger's discussion do not produce any appreciable increase in power limits and although these effects are small when the effect of the d-c. armature transient is also included in the analysis, the high-resistance damper increases the power limits above those shown in Fig. 3 by an amount greater than other types of dampers. High-resistance dampers should show up better, relatively, than these curves indicate. Open end rings would only be effective at the expense of increasing the recovery voltage.

Outdoor Switching Equipment
at Northwest Station Commonwealth Edison Company

BY W. F. SIMS[1] and C. G. AXELL[2]
Member, A. I. E. E. Associate, A. I. E. E.

Synopsis.—This paper describes the switching equipment and its arrangement in an outdoor switching center at 132, 66, and 12 kv., in connection with an installation of three-winding transformers. This installation is a junction point on an interconnected system, from which energy is distributed at the lower voltage.

The development of the original 12-kv. installation with indoor type of equipment enclosed in metal housings and concrete cells is described. The reasons leading to its extension with metal-clad oil-filled gear are also discussed.

A feature of this metal-clad oil-filled installation is that it is laid out on an isolated phase basis with wide separation between phases, which is the first time that this arrangement has been attempted with this type of equipment.

Included in the design are complete facilities for grounding and testing of the equipment, which are fully interlocked to insure maximum safety in their use.

A brief discussion of costs as compared with indoor installations is also given.

General

When the installation of the first 132-kv. underground cable to the Northwest Station of the Commonwealth Edison Company was planned, as a part of the interconnection of systems in the Chicago area, the design of suitable terminal arrangements became an important problem.

It was necessary to make provision not only for the 132-kv. equipment, but also for the connections of the transformers to the 12-kv. buses in the switchhouse and for additional 12-kv. feeders to serve the growing demand in this district. Consideration of the requirements of the development of the 66-kv. inter-station tie line system which would connect with both the 132- and 12-kv. systems, also had to be taken into account.

Studies of the problems involved resulted in the development of an outdoor installation with equipment to serve three different voltages, namely 132, 66, and 12 kv., of sufficient size to meet the present demands and to provide space for additional equipment at all three voltages for future needs. The terminal was designed on the isolated-phase basis with double buses on both the 66 and 12-kv. portions. Single-phase three winding transformers are centrally located between the 132- and the 12-kv. switch yards with the 66-kv. switch yard adjoining the 132-kv. installation. The terminal is located about 150 ft. east of the Northwest Station switchhouse, on the opposite side of a public street.

Fig. 1 shows the arrangement of this terminal with the present equipment, together with the space available for future extension.

The general diagram of connections is shown in Fig. 2.

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Presented at the Middle Eastern District Meeting No. 2, of the A. I. E. E., Philadelphia, Pa., October 13-15, 1930.

At present the terminal connects to two 132-kv. lines from the Waukegan Station, two 66-kv. lines from the Crawford Avenue Station and to sixteen 12-kv. lines to substations in the Northwest Station zone, with tie line connections to the indoor 12-kv. buses in the switchhouse. All of these lines are underground.

The circuit breaker control and the metering equipment are mounted on panels in the operating gallery of Northwest Station. The layout of the control wiring from the terminal to the gallery required careful attention. All of this wiring is in underground conduit and so located as to secure the best possible segregation between the wiring for different sections.

The control for the motor-operated disconnective switches is installed in weather-proof metal boxes, mounted on the structure, and in the case of the 132- and 66-kv. installations is so located that the operator can observe the operation of the switches.

132-Kv. Installation

In the selection of the breakers, calculations showed that they might be called upon to interrupt the circuit, under certain conditions of system operation, with voltages as high as 145 kv. Therefore circuit breakers of the 154 kv. class were chosen for this service. On the basis of calculated three-phase instantaneous short-circuit conditions a rated interrupting rating of 1,500,000 kv-a. at 154 kv. was specified.

Each breaker consists of three outdoor single-pole 600-ampere wheel mounted tanks, each provided with a separate solenoid operated mechanism, both mechanically and electrically trip free. The three poles are only electrically interlocked, with the operating coils connected in parallel.

Bushing type multi-ratio current transformers are mounted in the tanks for the recording and indicating switchboard instruments and for operating the relaying system.

The breaker poles are installed between concrete walls with the poles of like phase grouped together, the center to center spacing being 16 ft., 8 in.

30-169

Oil drain and supply piping has been installed with arrangements for portable flexible connections to the switch tanks. This piping is connected to underground tanks which, with the necessary pumping and filtering equipment, are located convenient to a nearby railroad track.

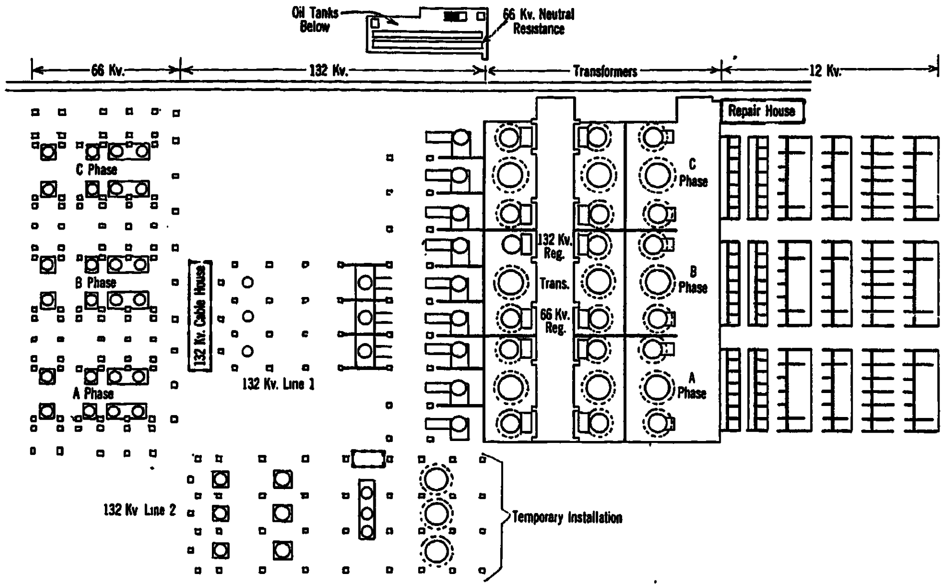

Fig. 1—General Arrangement of Outdoor Terminal
Northwest Station

All disconnective switches are made up of three single-pole motor-operated elements, connected in parallel for simultaneous operation and a minimum gap of 53 in. between live parts when in the open position.

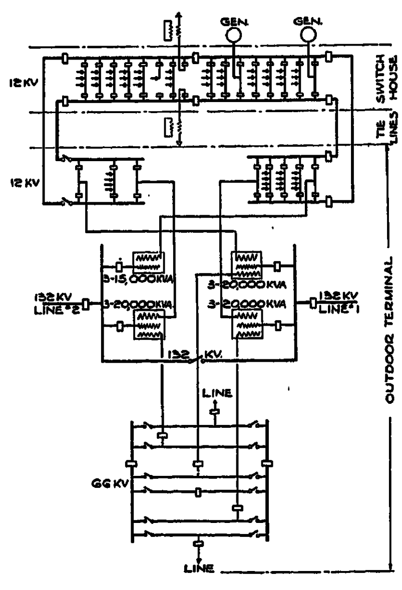

Fig. 2—General Diagram of 132-, 66- and 12-kv. Connections
Northwest Station

Motor-operated grounding switches are installed for grounding the lines and transformers, with the control circuits so arranged that each phase will be grounded separately. These are both mechanically and electrically interlocked with the corresponding disconnective switches so that neither can be closed unless the other is fully open. A low-voltage knife switch is installed on the ground side of each line grounding switch, so that the latter may be disconnected from ground and used for applying low voltage tests to the cables.

66-Kv. Installation

In the layout of the 66-kv. switch yard, it was necessary to provide for considerable flexibility in so far as bus sectionalizing is concerned, so that in the ultimate installation the proper distribution of transmission lines and transformers on the bus sections may be secured.

As shown in Fig. 3, the switch yard is divided into three zones each 54 ft. wide and containing the equipment for one phase.

The layout of the 66-kv. buses is on the isolated phase basis with a main and an emergency bus. Each bus is divided into two sections so as to conform to the general scheme of sectionalizing of the system.

The supporting structure is made up of simple columns and cross connections using standard beams and channels. For each phase the structure is in three parts, with solidly grounded double metal screen barriers between adjacent phases for the entire length of the structure, in order to prevent any possible flashover between phases. The central part, which is insulated from ground, supports the buses and connections and is not tied in with the two outer parts. These two parts are both grounded. On one part are mounted the 66-kv. cable potheads, potential transformers and disconnective switches for the transformer connections and the other supports similar equipment for the 66-kv. lines.

The ungrounded center section of this steelwork is used as a fault bus for the protection of the 66-kv. buses and disconnective switches connected thereto.

As in the 132-kv. installation three single-pole separately operated, electrically interlocked breakers are used for each three-phase unit. The operating coils are in parallel and no mechanical interlock is used. These breakers have a rated interrupting capacity of 1,000,000 kv-a. at 66 kv.

Due to the use of a 30-ohm neutral resistor, the possible voltage to which the breakers may be subjected under fault conditions, with the regulating transformers in the position of maximum boost, will be of the order of 76 kv. This determined the selection of 88-kv. breakers, which is the nearest manufacturer's rating above this value.

supports are required for the buses as the selector disconnective switch insulators serve for that purpose, the disconnective switches being installed horizontally on the top of the structure.

All disconnective switches are made up of three single-pole motor-operated elements with the motors connected in parallel. Those for the lines and transformers are equipped with a motor-operated grounding blade, insulated for 7,500 volts and are individually operated. These are mechanically and electrically interlocked with the main blades. Provision is made for connecting low-voltage test circuits to the line cables through the grounding blades. The motor-operated grounding blades on the bus section switches which are used for grounding the buses, are also similarly fully interlocked.

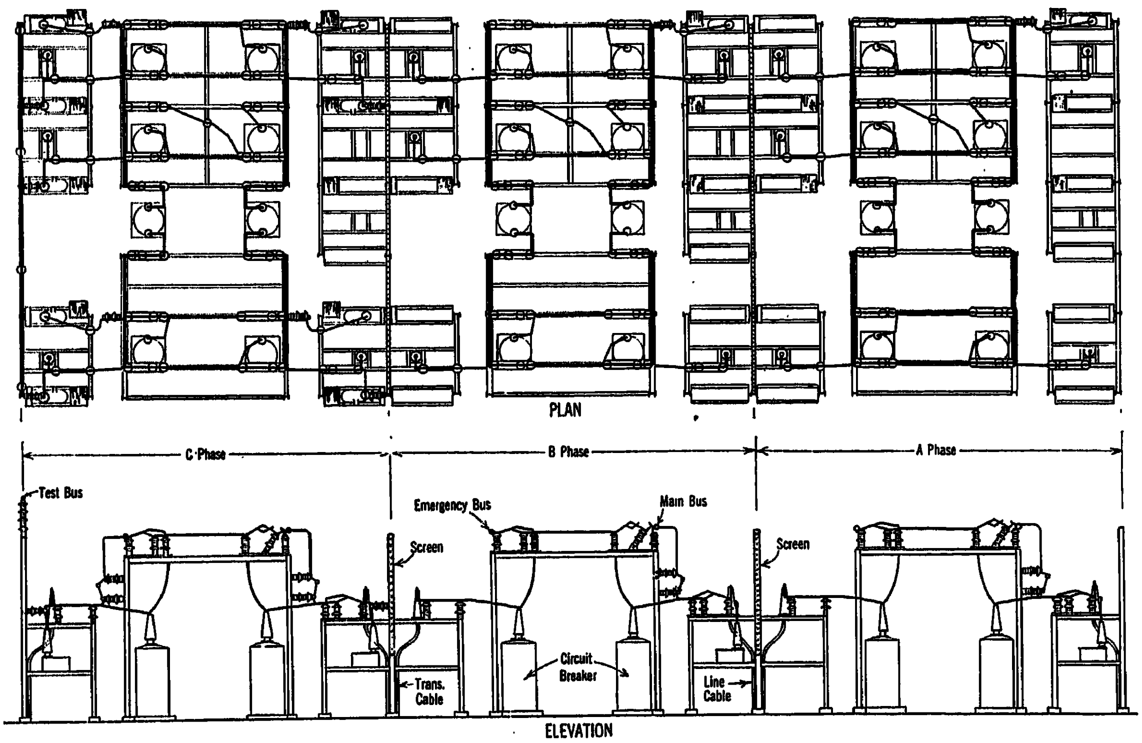

Fig. 3—General Arrangement of 66-kv. Isolated Phase Terminal
Northwest Station

Each breaker pole is individually frame mounted with tank lifting devices for lowering the oil pots for inspection and repair. The line and transformer breakers have multi-ratio bushing current transformers for relays and meters. Only one three-phase oil circuit breaker is installed for each transformer and for each line, the connections between these breakers and the buses being made through two sets of selector disconnective switches.

These single-pole breakers are arranged in two rows for each phase, located between the main and emergency buses. This makes a very simple layout for the connections between the breakers and the disconnective switches and allows ample space for the removal of the tanks. With this arrangement no extra insulator

12-Kv. Metal Housed Installation

There was no space available in the switchhouse for the additional 12-kv. switching equipment required. On account of space limitation, an extension of the building on the isolated phase basis could not be worked out satisfactorily and sufficient room was not available to provide for expected future requirements. These conditions together with the rising costs of building construction, led to a study of the possibility of an outdoor 12-kv. installation, in connection with the high-voltage transmission terminal where sufficient space was available to provide for the probable ultimate needs. Preliminary studies indicated that a satisfactory layout could be made on an isolated phase basis, with breakers of adequate rupturing capacity,

which could be located within a short distance of the power transformers.

The original idea was to make a conventional type of outdoor installation using standard outdoor equipment. Estimates of cost indicated a probable saving as compared with the indoor installation including the cost of building. As a higher degree of reliability of service was required than could be realized with a conventional grouped phase-open bus type of outdoor structure, a modification in design was brought about. This developed into an isolated phase installation with the breaker equipment mounted in steel housings installed in concrete compartments. The estimated cost of this design as developed, including the additional breakers required for tie lines, approximated that for a standard isolated phase indoor installation with the building cost included. However, the apparent possibilities of the outdoor scheme and the expectation that the future development of the project would tend to reduce these costs, together with the fact that an extension of the present switchhouse would include the cost of additional space for future installation, led to the decision to make a trial installation of 12-kv. equipment on this basis.

The first installation, which used a standard type of indoor breaker installed in a metal housing, provided for two 60,000-kv-a. banks of transformers, four 12-kv. distribution lines and two tie lines to the indoor 12-kv. buses. The scheme of connections follows the usual layout in all of the generating stations of the company. This provides for two main buses with line buses accommodating four distribution lines each, connected through group breakers to the main buses, with circuit breakers for connecting the transformers to either of the main buses. Six hundred ampere breakers are used for the lines, 2,000-ampere for the group switches and 3,000-ampere for the transformers and tie lines.

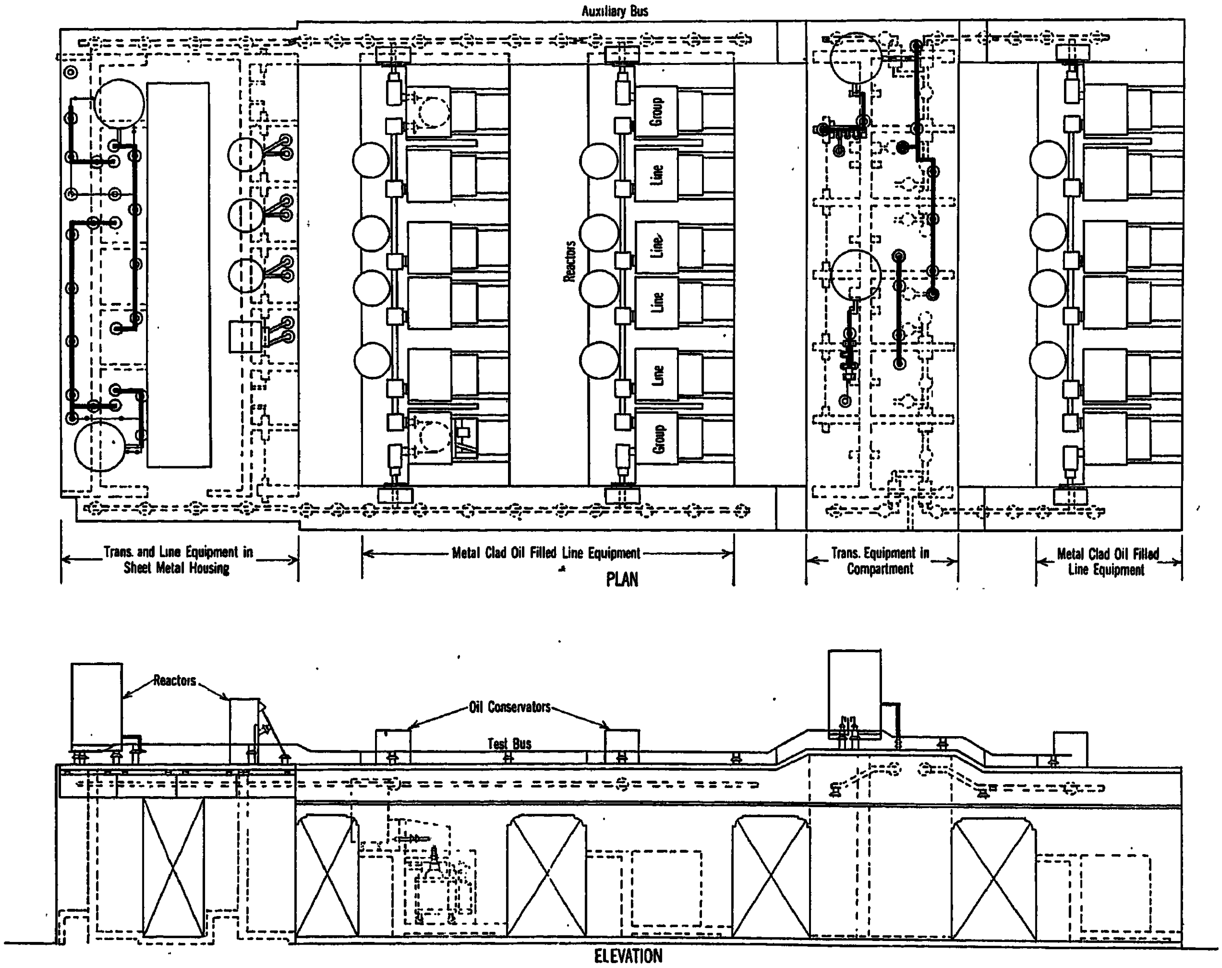

FIG. 4—GENERAL ARRANGEMENT SHOWING ONE PHASE OF 12-KV. ISOLATED PHASE INSTALLATION

Northwest Station

The equipment for each phase occupies a space of 40 ft. in length with 10-ft. aisles between phases. This corresponds to the phase segregation in the 66-kv. switch yard. Fig. 4 shows the general arrangement.

There are two concrete structures for each phase 7 ft. 8 in. wide and 15 ft. high with an operating space of 5 ft. 7 in., between structures. In each structure there is a longitudinal wall to separate the mechanisms and the testing and grounding equipment from the breaker tanks. Concrete barriers on the breaker side of the division wall, provide cells for seven single-pole

breakers in each structure. There are no barriers on the mechanism side of the division wall.

The breaker tanks and the disconnective switches are mounted in sheet metal housings 1/8 in. in thickness, which are installed in the concrete cells and are insulated from the concrete by porcelain insulators good for 7,500 volts, in order that the housings may serve as an integral part of the fault bus system. Access to the breakers is given through a double hinged door in the lower part of the housing with a small single door in the upper portion to give access to the disconnective switches. Weather proof strips cover the space between the housings and the concrete. The compartments on the opposite side of the longitudinal wall are also enclosed by weather proof metal doors, and house the operating mechanisms for the circuit breakers and the motor-operated disconnective switches. The test and ground buses with the necessary selector knife switches for grounding and testing, are also installed in these compartments. The mechanisms for the oil circuit breakers and the disconnective switches are mechanically interlocked to prevent improper operation, and the selector knife switches for grounding and testing are interlocked with the disconnective switches. To prevent condensation, space heaters are installed in all compartments.

The main buses, which are designed for 6,000 amperes, are installed in compartments carried across the ends of the structure near the top. They are made up of eight copper bars of 4 in. by 1/4 in., arranged to form a hollow square section and are supported on pin type insulators having a dry 60-cycle flashover of 70 kv. and a tensile strength of 12,000 lb.

Reactors of the outdoor type for the lines and transformers are mounted on the top slab of the structure. The connections to these reactors are carried through this slab in roof type bushings.

Cables and control conduit and wiring are carried through an open space below the ground level. Terminal boards for the control and instrument wiring are mounted in weather proof metal boxes at the ends of the structure.

Circuit breakers of the indoor type having a rated interrupting duty of 800,000 kv-a. at 12 kv. and insulated for 25,000 volts, were selected. This voltage rating, which was also used for the bus and disconnective switch insulators, was chosen in order to obtain a high margin of safety. This was deemed necessary as there was no assurance of entire absence of moisture in the housings and as this was the first outdoor 12-kv. installation on the system, especial attention was given to the insulation.

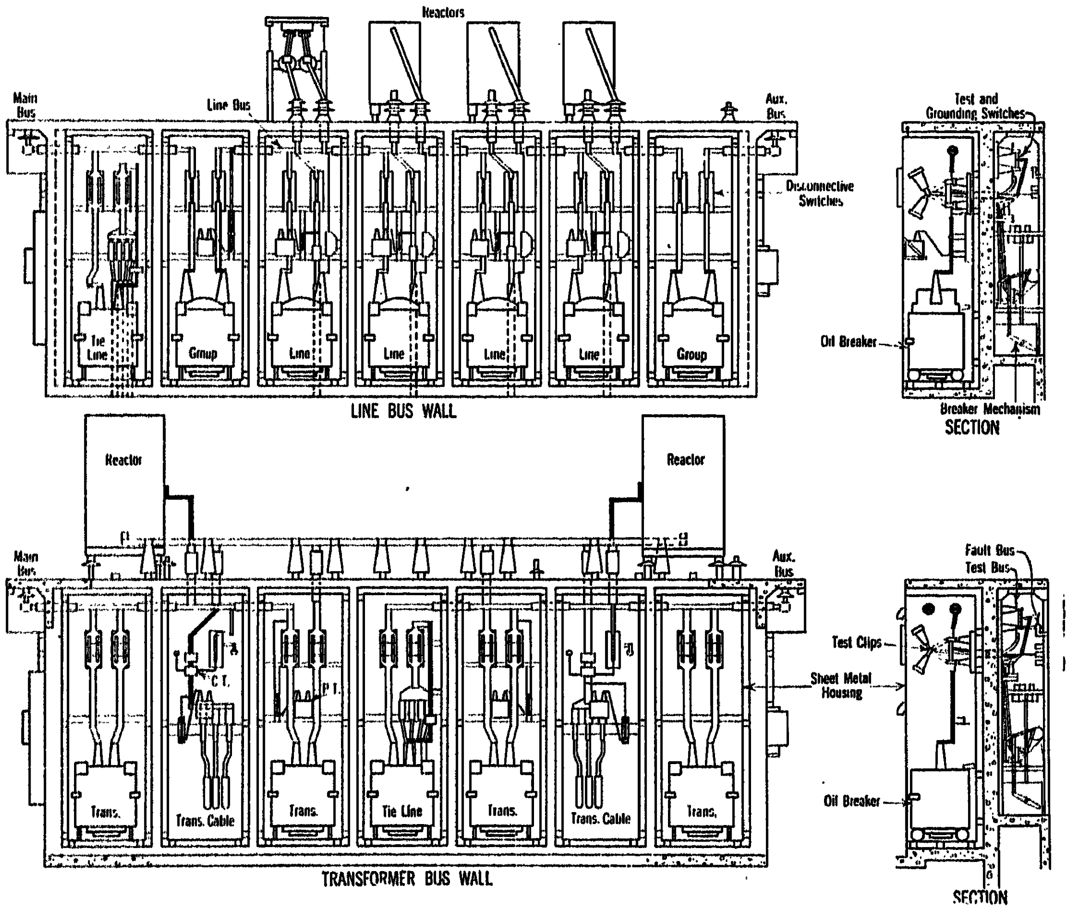

FIG. 5—ELEVATIONS AND SECTIONS OF ONE PHASE OF 12-KV. INSTALLATION IN SHEET METAL HOUSINGS
Northwest Station

Each three-phase breaker consists of three single-pole units installed on 50-ft. centers with separate mechanically trip free mechanisms, the solenoids of which are connected in parallel for simultaneous operation. An operating relay controls the operation of each pole.

Each pole is truck mounted, with roller bearing wheels and provision is made for securely holding the trucks in position on the rails in the housing. The breaker tanks may be withdrawn from the housings on to a transfer truck having a motor-operated winch. A repair house located adjacent to this installation, equipped with a hoist and oil piping connections affords the necessary maintenance facilities.

The circuit breakers and the disconnective switches are connected to their respective mechanisms in the rear compartment by means of insulated rods, which pass through gas proof gaskets mounted in castings set in the concrete wall. The operating mechanisms hand operation, when in the open position, for further movement to the test or ground position. This operation is completely interlocked to prevent improper operation.

The testing and grounding switches together with their operating rods and interlocks are alike for all circuit breakers and form a unit assembly. This feature greatly facilitated their installation.

The ground bus is insulated from the structure and is connected to ground through the fault bus, so that in the case of accidental grounding of a live bus, the system will be cleared by the operation of the fault bus relays.

Fig. 6 shows a single-phase diagram of the 12-kv. layout with the testing and grounding connections.

This installation is equipped with complete fault bus protection. As already noted, the steel housings within which the oil circuit breakers, disconnective switches and the current and potential transformers

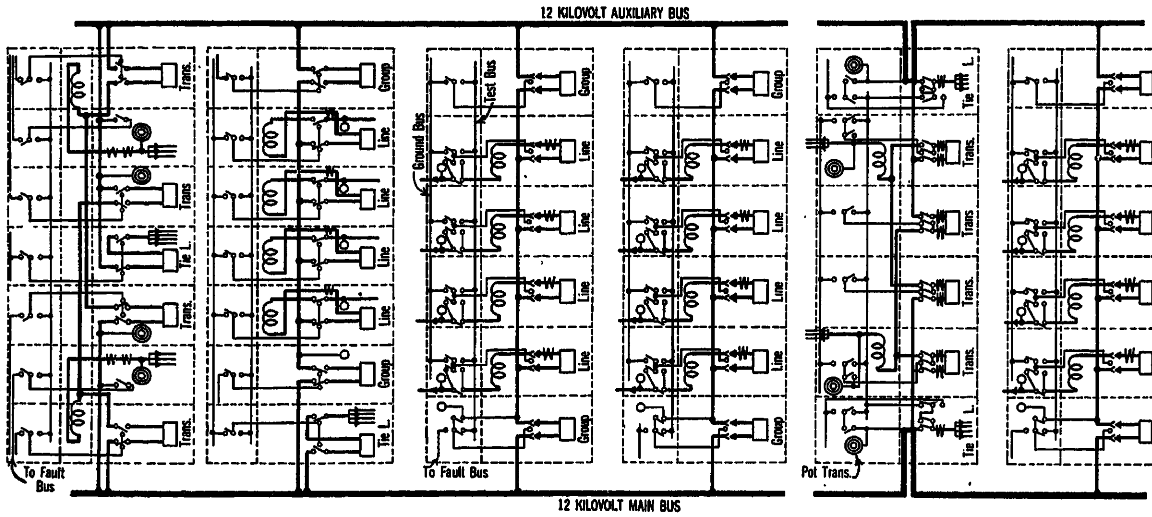

FIG. 6—SINGLE-PHASE DIAGRAM OF 12-KV. CONNECTIONS
Northwest Station

with rods and connections are the same for all sizes of breakers used, which permit complete interchangeability of equipment.

Bolted connections are used between the breaker poles and the motor-operated disconnective switches, which are installed in the same housings, directly above the breakers. These disconnective switches have the same carrying capacity as the breakers to which they are connected and are operated as a two-pole unit. Insulated operating rods connect these switches to the motor mechanisms, through gas tight gaskets.

The design of this installation included complete facilities for the grounding and testing of all 12-kv. buses, transformer leads, tie lines, distribution lines and circuit breakers. By means of lever-operated knife switches in connection with the disconnective switches the desired equipment can be connected for either grounding or testing. For this operation the disconnective switch can be changed from motor to are mounted, and through which the line bus copper passes, are an integral part of this system. All housings are completely insulated from ground, excepting where predetermined ground connections were made, so that there will be no parallel path for fault current to flow to ground. For this reason, insulated sections were installed in the conduit for all wiring entering the housings. The sheet metal covers of the main bus compartments also form a part of the fault bus, which is so sectionalized that in the event of a fault, a minimum of equipment will be taken out of service.

12-KV. METAL-CLAD OIL-FILLED INSTALLATION

Since the installation of the equipment described above was made, the developments which had taken place in the design of metal-clad oil-filled switch gear led to the consideration of this type of equipment when the need for additional 12-kv. facilities became apparent. Up to this time no such installation had been

made on the isolated phase arrangement, but it was thought that such an arrangement could be worked out and installed at a cost not materially greater than that for the previous outdoor installation.

With the active cooperation of the manufacturer's engineers an intensive study was made and an isolated phase design that met the space limitation established by the previous installation was finally developed. In working out this design, efforts were made to avoid unnecessary complications and a relatively simple arrangement was secured.

This project differs from other metal-clad installations in several particulars. It is the first installation of this type built with the isolated phase arrangement and the breakers are withdrawn horizontally instead of being lowered. This feature greatly simplifies the design. The oil-filled line buses are supported on a concrete wall, which also supports the line reactors and the grounding and testing equipment. Owing to the difficulty of designing metal-clad oil-filled buses for over 3,000 amperes capacity, the main buses are similar to and a continuation of the buses in the installation previously described. These differences in no way reduce the safety features of the conventional metal-clad gear. In addition there is included in this project an installation of four circuit breakers for transformer connections installed in open concrete compartments with open type copper bar connections to the main buses.

The oil-filled equipment has been installed as a continuation of the original 12-kv. installation and the general layout is along similar lines. The main buses are carried in enclosed concrete compartments 12 ft. above the ground, supported on concrete walls, and are in line with the buses of the first section. Openings through these walls give access to the operating space in front of the breakers. Transverse concrete walls 7 ft. 8 in. in height, for supporting the oil-filled line buses and equipment, are installed across the space between the main bus walls. Concrete barriers forming six compartments have been built at the rear of these walls, in which the 12-kv. cable terminals, the oil-filled cabinets containing the testing and grounding switches, and the potential transformers are installed. No concrete barriers have been installed between the oil circuit breaker tanks, except between the group breakers, and the adjacent line breakers, for segregation of fault bus operation. An open space below the ground level provides space for conduit and cable runs. Fig. 7 shows a section and elevations of this arrangement.

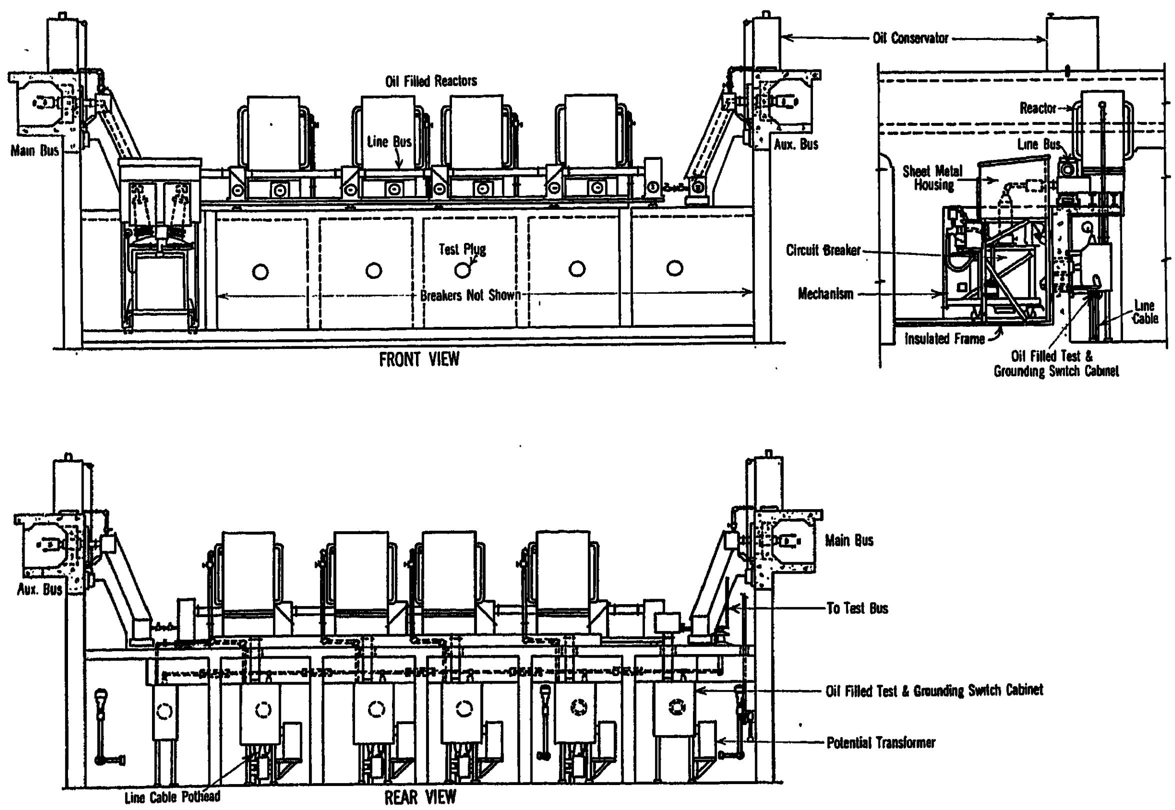

FIG. 7—SECTION AND ELEVATIONS OF ONE PHASE OF 12-KV. METAL-CLAD, OIL-FILLED INSTALLATION
Northwest Station

In contrast with the original 12-kv. outdoor installation, outdoor type of equipment is used. The breakers selected have a rated interrupting duty of 900,000 kv-a. at 12 kv. and are equipped with bushings having a 60-cycle wet flash-over value of 60 kv. Each three-phase breaker consists of three truck mounted single-pole units installed on 50-ft. centers, each equipped with

a solenoid operated mechanism which is both mechanically and electrically trip free. The mechanisms are mounted in sheet metal housings supported on the truck with space heaters in the housing to prevent condensation.

The breaker and wheel mounted truck assembly is of the horizontal draw out type installed on rails which are an integral part of a rigid frame work, insulated from ground, on the upper part of which is supported a sheet metal housing enclosing the stationary bushings and contacts with which the contacts on the bushings of the circuit breaker are engaged. This housing is equipped with automatic shutters which are operated by the withdrawal or replacement of the breaker truck and protect the live parts from accidental contact under all conditions. The breaker mechanism is so interlocked that the breaker cannot be withdrawn or replaced unless it is in the open position. Bushing type current transformers are installed in the tanks of the line breakers. Self alining contacts are used on the bushings of all circuit breakers for engaging the clip on the stationary contacts. A terminal board is mounted on each truck to which the wiring from the operating mechanisms and current transformers are connected. Two multi-conductor flexible cables with plugging devices, one of which carries the current transformer wiring and the other the control wiring connect from the terminal board to the stationary part of the installation. A separate cable connects to the space heater. These cables are of sufficient length to permit electrical operation for testing the breaker when it has been withdrawn from the operating position. An interlock prevents the disconnection of the current transformer wiring unless the breaker is in the open position, and has been withdrawn.

A sliding contact connects the breaker truck to the fault bus system when the switch is in position.

A levering device on each truck facilitates the engagement and disengagement of the primary contacts without shock or excessive strain on any of the parts. This device engages when the primary contacts are approximately 4½ in. apart. It also securely latches the truck in the operating position by means of a toggle action. The breakers are withdrawn and handled by the truck previously described.

The scheme of connections of the knife blade switches for testing and grounding is similar to that previously described in the original 12-kv. installation excepting for necessary modifications due to the absence of separate disconnective switches at the circuit breakers. These switches are enclosed in oil-filled metal cabinets, mounted on the rear of the structure, behind the oil breakers. A disconnective switch to which the line cable is connected, is also mounted in each cabinet in connection with the line breakers. The grounding and testing switches are operated by means of two shafts, with a separate shaft for operating the line disconnective switch, passing through oil tight bushings, with indicating devices to show the position of the switches. This equipment is fully interlocked so that these switches cannot be moved while the oil circuit breaker is open and the breaker cannot be closed unless these switches are in the proper position. The interlock also prevents their operation unless the line disconnective switch is open.

A test connection is brought out from the test cabinet through an oil tight bushing, to the breaker side of the concrete wall, to which a flexible cable may be connected for applying test pressure to the breaker when it has been withdrawn from the operating position. This test contact is covered by a hinged door which cannot be opened unless the breaker has been withdrawn. Cable potheads are bolted to the bottom of these cabinets through which the 12-kv. single conductor line cables are brought for connection to the line disconnective switches. The necessary oil-filled potential transformers are also mounted in these compartments with their connections made in the cabinets into which they are carried through oil tight bushings.

The grounding and testing switches for the line buses are electrically interlocked with the group switches so that they cannot be operated unless both group breakers are in the open position. This interlock also prevents the group switches from being closed unless the testing and grounding switches are in normal open position.

The oil-filled line bus assembly consists of a copper bus enclosed in copper tubing with aluminum alloy connecting boxes, the oil conservators and the primary disconnective bus contacts. This assembly is divided into three sections, the line bus assembly, and the two connections to the main buses. The line bus which supplies four 12-kv. distribution lines is made as a unit with flexible joints and is mounted on a welded angle iron frame of rigid construction. The connections to the two main buses are in separate aluminum alloy boxes. These three sections are insulated from the concrete supporting structure and from each other and form parts of the fault bus system. The entire bus system is filled with oil on which a constant pressure is maintained by the conservator tanks located at each end. The oil is carried to the system through connecting pipes with suitable valves and insulating couplings.

The connection boxes which are of heat-treated cast aluminum alloy form the supports for the line bus and bus connections.

The line bus is made up of sections of hard drawn copper tubing 3½ in. in diameter, with a carrying capacity of 2,000 amperes, of the proper lengths required to span the distance between two adjacent switch units. It is insulated with machine wrapped micarta paper impregnated with varnish and has flexible connections to the disconnective bushings. The bus is supported in micarta collars grooved to permit circu-

lation of oil which center the bus in the tubing. Micarta stops are provided to limit the travel of the bus in one direction if there is a tendency to crawl due to expansion. All connections from the line bus are carried out of the connecting boxes through oil tight porcelain bushings.

The conservator tanks are equipped with a gage glass, a low oil level alarm and a dry air breathing device.

The current limiting reactors for the 12-kv. lines which are of 450-ampere capacity and ½-ohm reactance are of the air core, metal clad, oil immersed type, with connections brought out at the bottom of the tank. Each reactor tank serves as an oil conservator for the testing and grounding switch cabinet.

Reference has been made to circuit breakers for two transformer banks installed in connection with this project which are not of the oil-filled type. This arrangement was made because the carrying capacity required in their connections is such that a satisfactory design of oil-filled equipment could not be worked out, as was also the case with the main buses. These breakers and their disconnective switches are of the outdoor type installed in concrete compartments similar to the original 12-kv. installation with the exception of the metal houses which are omitted. The switch compartments are enclosed by hinged ventilated doors connected to the fault bus system with flexible shunts around the hinges.

Conclusion

The metal housed equipment has been in service for about three years and the metal-clad oil-filled for about eight months. The operating experience with both installations has so far been entirely satisfactory and with the possible exception of maintenance difficulties under severe weather conditions, is fully as convenient to operate as an indoor installation. The degree of safety both to life and service that can be secured in the outdoor design is as high as that in an indoor installation. The distance by which adjacent phases may be separated is such that the liability of trouble spreading is much less than would be the case in a similar installation located in a building. Any arc or explosion that might occur would not be confined in an enclosed space and the amount of damage that might result should be reduced to a minimum.

Preliminary estimates had indicated the possibility that a 12-kv. outdoor installation should cost less than one indoors, with the cost of building included. Exact comparisons are difficult to make because of varying conditions on different projects. However, an analysis of actual cost figures of both kinds of installations with allowances made to place their costs on a comparable basis showed that there was very little difference in the final cost. The metal housed type cost slightly less and the metal-clad oil-filled type slighty more than a standard indoor isolated phase installation.

As these outdoor installations were along new lines, considerable developmental work was required which necessarily had an effect upon the cost. Future installations of this character, should show a tendency toward lower costs, provided that a reasonable degree of standardization and duplication of equipment can be secured.

Discussion

W. W. Edson: Installations of this type having the three phases separately operated and not mechanically interlocked should in some cases be considered with respect to the type of line relays used. Thus, for parallel lines, if one of the incoming breakers should not be uniform in closing, there will be a short interval of time in which one of the phases is open, thereby causing an unbalanced condition in the lines. A sensitive high-speed relay either in the ground residual circuit or in a cross-connection between the phases of the parallel lines might operate and improperly trip one or both lines.

R. A. Hentz: The paper indicates that while there are two 12-kv. buses, the selection of which is through oil circuit breakers, this is not the case of the 66-kv. or the 132-kv. sections. In the 66-kv. section the two buses are selected by disconnecting switches with one oil circuit breaker per line or transformer bank, and in the 132-kv. section there is but a single bus sectionalized with a disconnecting switch.

From an inspection of Fig. 3 there does not seem to be any provision for a second oil switch in the 66-kv. section and from Fig. 1 there appears to be no means of double busing in the 132-kv. section, either by two oil circuit breakers or one oil circuit breaker and two sets of disconnectors. Apparently the authors believe the extra flexibility obtained by double busing is not worth the cost. I would be interested to hear further comment on this point.

W. F. Sims and C. G. Axel: The bus arrangement in the 66-kv. transmission terminal provides for a main bus for regular operation and an emergency bus for use only during abnormal conditions. The main bus is divided into two principal sections, which division runs through the entire system. The installation of selector oil circuit breakers between the main and emergency buses for each 66-kv. line and transformer bank was not considered to be justified in view of the materially increased cost of such an arrangement. As will be noted from the bus diagram, it is possible to connect these two buses through the tie switch after which it is possible to transfer a line or transformer bank by manipulation of the disconnective switches, which gives sufficient flexibility to meet the conditions of service and saves the cost of the additional breakers.

The 132-kv. installation is a part of a general interconnected system with sufficient reserve on the 66-kv. supply to take care of an outage on the 132-kv. bus, as both systems supply the same banks of three-winding transformers which feed into the 12-kv. distributing buses. For this reason the expense of a double bus arrangement on the 132-kv. installation was not considered justified.

A New System of Speed Control
For A-C Motors

BY A. M. ROSSMAN[1]
Fellow, A. I. E. E.

Synopsis:—The drive unit of this system consists of a constant speed a-c. motor supplemented by an adjustable speed d-c. machine of much smaller size. Both rotor and frame of the a-c. motor are mounted on bearings. The d-c. machine is mechanically connected to the frame of the a-c. motor so that the d-c. machine may drive or be driven by the frame. The d-c. machine is electrically connected through a motor-generator set of equivalent rating to the source of alternating current energy. The shaft speed of the a-c. motor is increased above the fixed speed by rotating the frame of the a-c. motor in the same direction as the rotor. The shaft speed is decreased by rotating the frame in the opposite direction. The direction of rotation and the speed are governed by adjusting the voltage impressed on the armature of the d-c. drive machine by the generator of the motor-generator set. When the unit is used to drive fans, the speed range is obtained by a combination of armature voltage control and field control of the d-c. drive machine. This permits a still further reduction in the rating of the d-c. drive machine so that for comparatively wide ranges of speed it forms but a small percentage of the total drive unit rating.

Twenty-four units of this type, aggregating 7,020 hp., are now being built for Powerton Power Station for driving forced and induced draft fans. This system of fan drive is being installed in preference to the two-speed squirrel-cage type induction motor system previously used, because it shows large savings in energy, costs little more, and provides a simple method of fan control which permits the adoption of a simplified system of automatic combustion control. Energy savings and investment costs are given in detail. The versatility of the system is further illustrated by a description of a 2,500-hp. unit of this type designed to drive a high-pressure reciprocating boiler feed pump.

During the first seven months of 1930, orders were placed for 35 of these units ranging in size from 166 hp. to 2,500 hp., aggregating 16,000-hp. for installation in four different power stations.

* * * * *

Description of the Motor and Speed Control Equipment

The drive unit of this system consists of a constant speed a-c. motor of either the synchronous or induction type, supplemented by an adjustable speed d-c. machine of much smaller size. The frame of the a-c. motor is mounted on bearings so that the frame as well as the rotor may rotate. The d-c. machine which is shunt wound but separately excited is mechanically connected to the frame of the a-c. motor so that it may drive or be driven by the frame. The d-c. machine is electrically connected through a motor-generator set of equivalent rating to the source of alternating current energy. Fig. 1 shows a typical diagram of the machines with their electrical connections. Fig. 2 shows a typical arrangement of the drive unit.

Method of Operation

The speed of the driven machine is increased above the fixed speed of the a-c. motor, which will be called the base speed, by causing the d-c. machine acting as a motor to drive the frame of the a-c. motor in the same direction as the rotor. The speed of the shaft is then the sum of the base speed plus the frame speed. The speed of the shaft is decreased below the base speed by causing the frame of the a-c. motor acting as a motor to drive the d-c. machine as a generator in the direction opposite to that of the rotor. The shaft speed is then the difference between the base speed and the frame speed. The d-c. machine then delivers energy through the motor-generator set back into the a-c. system.

The direction of rotation and the speed of the d-c. drive machine are governed by holding constant excitation on its field and adjusting the voltage impressed on its armature terminals by the generator of the motor-generator set. The range of d-c. voltage is from

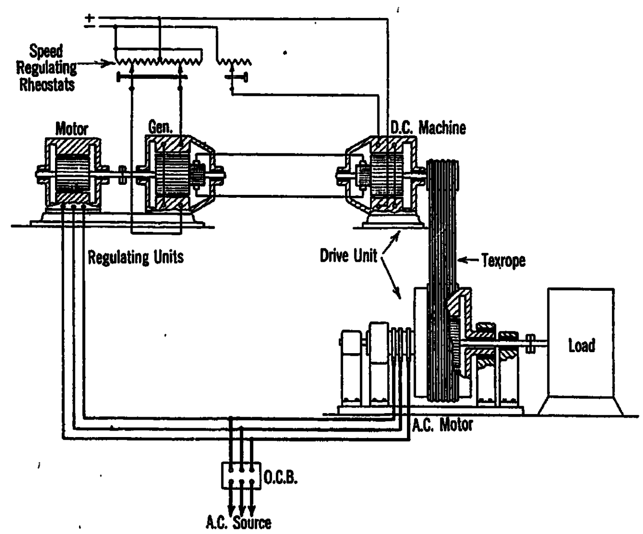

Fig. 1—Diagram of New System of Adjustable-Speed Drive

maximum positive, through zero, to maximum negative. This voltage is controlled by a rheostat inserted in the field circuit of the generator. The armature current does not reverse when the voltage is reversed.

Extension of the Speed Range

Where this system is used to drive fans (or centrifugal pumps), machines in which the power is a func-

1. Research Engineer, Sargent & Lundy, Inc., Chicago, Illinois.

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tion of the cube of the speed, the speed range may be extended beyond that attainable by armature voltage control, by weakening the field of the d-c. drive machine. The field strength is controlled by a rheostat inserted in the field circuit. The use of field control of the d-c. drive machine to furnish a part of the speed range decreases the spread between the rated speed of the

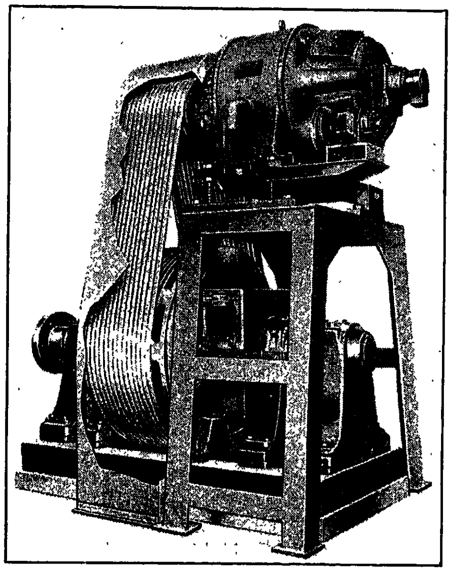

FIG. 2—430-HP. 2,200-VOLT 60-CYCLE THREE-PHASE 1088/444-REV. PER MIN. VARIABLE-SPEED DRIVE UNIT

a-c. motor and the maximum operating speed of the fan. As the apportioning of the rating of the drive unit between a-c. motor and d-c. machine is determined by the percentage of speed which each machine contributes to the maximum operating speed (which is coincident with maximum load) of the fan, a decrease in the spread means a corresponding decrease in the percentage of rating of d-c. machine in the drive unit

TABLE I

Proportioning of the drive unit between a-c. motor and d-c. machine under various combinations of armature voltage control and weakened field control of the d-c. drive machine to give a speed range of 100 to 50 per cent.

Ratio max. speed / rated speed	D-c. machine: No. of units of speed range accomplished by— Armature voltage control: Positive	Negative	Weakening the field	Rating of: A-c. motor	D-c. machine
1/1	0	1	0	100	50
1/1	1	0	0	50	50
1/1	1	1	0	75	25
2/1	1	1	1	83.3	16.6
3/1	1	1	2	87.5	12.5
4/1	1	1	3	90	10

Note: Full torque is available with full field and armature voltage control; torque should be reduced in direct proportion to the amount of field weakening.

and an equivalent decrease in the size of the speed regulating motor-generator set. These relations are shown in Table 1. The last three rows of figures show the apportioning of the drive unit rating between a-c. motor and d-c. machine corresponding to three different degrees of field weakening of the d-c. drive machine.

As the d-c. motor designed to give a 3/1 speed range by field control is a recognized standard machine, it has been chosen as the basis for determining maximum fan speeds corresponding to various speeds of the a-c. motor for those ranges of fan speed which exceed 100 to 57½ per cent. For ranges of fan speed less than 100 to 57½ per cent, the amount of field weakening must be reduced to prevent overloading of the d-c. drive machine.

TABULATIONS OF FAN SPEEDS AND MOTOR RATINGS

Table II shows the maximum operating speed of the fan or pump corresponding to the two variables which determine it, *viz:*

(1) The speed of the induction motor;

(2) The speed range of the load.

TABLE II

The following data apply to fans and centrifugal pumps, machines in which the power varies as the cube of the speed.

The table shows the maximum speed of the fan or pump corresponding to the two variables which govern it, viz:

1. **Speed of squirrel-cage type induction motor.**
2. **The speed range of the fan or pump.**

The table also shows for each speed range the relative sizes of induction motor and d-c. machine which together make up the drive unit.

The speed range is obtained by a combination of armature voltage control and field weakening of the d-c. drive machine. For ranges greater than 100 to 57.5 per cent, one-half the total range is obtained by each method. For ranges less than 100 to 57.5 per cent the proportion obtained by field weakening must be decreased to prevent overloading of the d-c. drive machine. The method of determining the limiting value of field weakening and the method of correcting for slip corresponding to variatons of load are given on the next table.

Speed range—100 per cent to......(per cent)		95	90	85	80	70	60	50	40	30	20	10
Speed reduction in per cent of max. (per cent)		5	10	15	20	30	40	50	60	70	80	90
Relative ratings of machines of the drive unit	A-c.	97.4	95.1	93.2	91.6	89.5	88.7	86.7	84.1	81.6	79	76.5
	D-c.	2.6	4.9	6.8	8.4	10.5	11.3	13.3	15.9	18.4	21	23.5
Induction motor: Syn. speed	Full-load speed	Maximum operating speed of fan or pump										
1800	1750	1800	1840	1880	1920	1960	1975	2025	2080	2150	2210	2300
1200	1160	1190	1220	1245	1270	1300	1310	1340	1380	1425	1470	1520
900	870	890	915	935	955	975	985	1005	1030	1065	1100	1135
720	690	710	725	740	755	775	780	800	820	850	875	905
600	575	590	605	615	630	645	650	665	685	705	725	750
514	490	505	515	525	535	550	560	570	585	605	620	640
450	430	445	455	465	475	485	490	500	515	530	550	565

TABLE III

The following data apply to fans and centrifugal pumps, machines in which the power varies as the cube of the speed.
The table shows the method of determining and the figures for—

(1) The slip of the induction motor at various loads. Full load slip is assumed to be 4 per cent for all motors.
(2) The amount of field weakening permissible without overloading the d-c. drive machine.
(3) The speed range obtainable with the d-c. machine.
(4) The relative ratings of the d-c. machine and the a-c. motor of the drive unit.

The letters used in the formulas are the serial letters in the first column of the table. In applying the formula substitute for the letter the figure in the corresponding speed range column.

a. Speed range 100% to ... %	95	90	85	80	70	60	50	40	30	20	10
b. Speed reduction in % of max. speed ... %	5	10	15	20	30	40	50	60	70	80	90
c. Torque at min. speed ($= a^2/100$) ... %	90	81	72	64	49	36	25	16	9	4	1
d. Correction for slip [$=4\ (1-c/100)$] ... %	0.4	0.8	1.1	1.4	2	2.6	3	3.4	3.6	3.8	4
e. Speed range by d-c. machine($=b+d$) .. %	5.4	10.8	16.1	21.4	32	42.6	53	63.4	73.6	83.8	94
f. Speed range by armature control ... Units	2	2	2	2	2	2	2	2	2	2	2
g. Speed range by field control ($=100/c-1$) Units	0.11	0.23	0.39	0.56	1.05	1.78	..	..	..	..	..
g. Speed range by field control ($= 2$) .. Units	..	..	..	..	..	..	2	2	2	2	2
h. Speed range total ($=f+g$) ... Units	2.11	2.23	2.39	2.56	3.05	3.78	4	4	4	4	4
k. Rating of d-c. machine ($=e/h$) ... %	2.6	4.9	6.8	8.4	10.5	11.3	13.3	15.9	18.4	21	23.5
m. Rating of induction motor ($=100-k$). %	97.4	95.1	93.2	91.6	89.5	88.7	86.7	84.1	81.6	79	76.5

The maximum operating speed of a fan or centrifugal pump operating on this system is determined by dividing the full load speed of the induction motor by the figure on line "*m*" in the corresponding speed range column.

This table also shows the relative ratings of induction motor and d-c. machine corresponding to each range of speed.

Attention is directed to the wide range of speed that can be obtained from a comparatively small percentage of d-c. machine rating in the drive unit. For example, a speed range of 100 to 50 per cent is obtained with a drive unit in which the rating of the d-c. machine is but 13.3 per cent of the total. If the a-c. motor were of the synchronous type, the rating of the d-c. machine would be but 12.5 per cent of the total.

Table III gives the list of constants used in computing the figures of Table II and the formulas for deriving these constants.

Extension of the speed range by field control is not practicable where horsepower varies directly with the speed; the full load speed of the a-c. motor then becomes the mid-point between maximum shaft speed and minimum shaft speed.

Equipment in the Powerton Power Station

An extensive installation of this system of speed control is now being made in the power station of the Super Power Company of Illinois at Powerton (near Pekin) Illinois. Here the forced and induced draft fans of six boilers are driven by motors which operate on this system. Each boiler has two forced draft fans and two induced draft fans. Each fan has its own independent drive unit. The a-c. motors of the drive units are of the squirrel-cage induction type.

The frame and the rotor are supported independently, each having its own pair of pedestal bearings. Hollow stub shafts, cast integrally with the end shield, support the rotating frame on the inner pair of bearings. The rotor is carried on a shaft which passes through the hollow stub shafts of the frame and is supported on the outer pair of bearings. All bearings are of the sleeve type. One of the hollow stub shafts is made sufficiently long to mount the three collector rings between the end shield and its bearing support. The collector rings and brush rigging are enclosed in a steel housing to prevent accidental contact with the live parts. Fig. 2 is a photograph of the Powerton induced draft fan drive unit.

One motor-generator set controls the two forced draft fans of each boiler, while a second motor-generator set controls the two induced draft fans.

The principal data pertaining to this installation are given in the following tabulation:

	Forced draft fans	Induced draft fans
Number of fans ...	12	12
Number of drive units ...	12	12
Maximum fan speed ...	1,004 r. p. m.	1,088 r. p. m.
Minimum fan speed ...	452 r. p. m.	435 r. p. m.
Range of fan speed ...	100% to 45%	100% to 40%
Constant-speed component (a-c. power) at maximum fan speed ...	141 hp. @860 r. p.m.	330 hp. @860 r. p.m.
Adjustable-speed component (d-c. power) at maximum fan speed ...	25 hp. @ 144 r. p. m.	89 hp. @ 228 r. p.m.
Total power at maximum fan speed ...	166 hp.@1004 r.p.m.	419 hp. @1,088 r.p.m
Speed of d-c. machine at maximum fan speed ...	Plus 625 r. p. m.	Plus 625 r. p. m.
Speed of d-c. machine (operating as a generator) at min. fan speed ...	Minus 1,875 r. p. m.	Minus 1,250 r. p. m.
Ratio of ratings—d-c. machine/a-c. motor ...	14.5/85.5	21/79
Number of speed regulating motor-generator sets ...	6	6
Rating of each speed regulating motor-generator set ...	40 kw.	150 kw.

Total rating of all drive units ... 7020 hp.
Total rating of all speed regulating motor-generator sets ... 1140 kw.

The a-c. motors are designed to operate at 2,200 volts, three phase.

The curves of Fig. 3 show the division of load between the a-c. motor and the d-c. machine over the speed range of the forced draft fans. Fig. 4 shows similar curves for the induced draft fans. These curves also show how the total speed range is apportioned between armature voltage control and field control of the d-c. drive machines. On the forced draft fans one-half the speed range is obtained by armature voltage control and one-half by field control; on the induced

draft fans two-thirds is obtained by armature voltage control and one-third by field control. The relatively small proportion of d-c. machines is reflected in the rating of the conversion equipment which, as shown

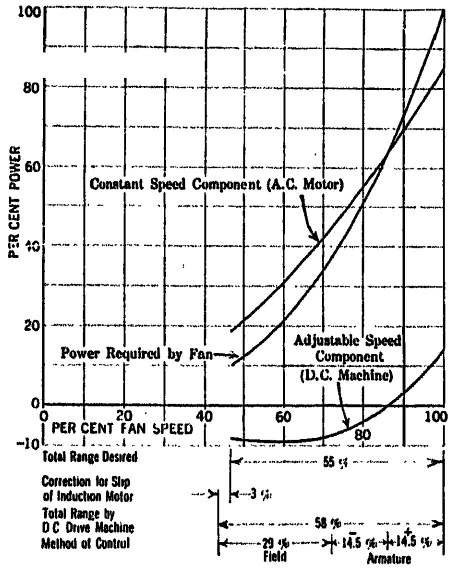

FIG. 3—POWER CURVES FOR FORCED DRAFT FAN

Maximum speed of fan	1,004 rev. per min.
Minimum speed of fan	452 rev. per min.
Rating of drive unit	166 hp.
Rated speed of a-c. motor	860 rev. per min.
Ratio of rating $\dfrac{\text{d-c. machine}}{\text{a-c. motor}}$	$\dfrac{14.5}{85.5}$

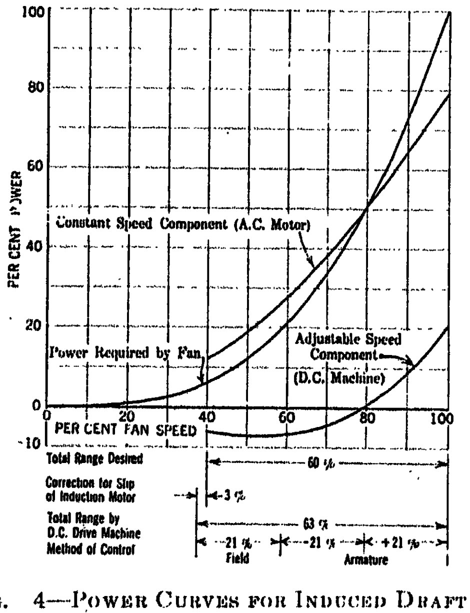

FIG. 4—POWER CURVES FOR INDUCED DRAFT FAN

Maximum speed of fan	1,088 rev. per min.
Minimum speed of fan	435 rev. per min.
Rating of drive unit	419 hp.
Rated speed of a-c. motor	860 rev. per min.
Ratio of rating $\dfrac{\text{d-c. machine}}{\text{a-c. motor}}$	$\dfrac{21}{79}$

by the above table, is but 1,140 kw. in motor-generator set capacity to control 7,020-hp. in motor capacity. An induced draft fan having a maximum speed of 1,004 rev. per min. would have still further reduced the rating of the motor-generator set capacity, but as the fans and building steel were on order for some time before it was decided to install this system of fan drive, the change was not regarded as practical.

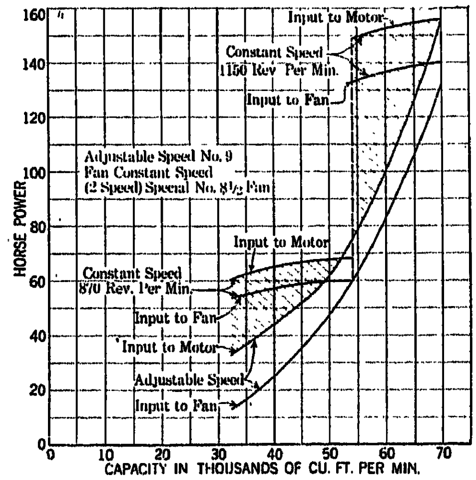

FIG. 5—COMPARATIVE PERFORMANCE CURVES FOR FORCED DRAFT FAN

REASONS FOR INSTALLING THIS SYSTEM AT POWERTON

The reasons for installing this system of driving the fans at Powerton are as follows:

(1) The simplicity and smoothness of the method of speed control.

(2) The energy saving due to the high efficiency of the method of control.

(3) The fact that the new system can be installed at nearly the same cost as the system previously used.

(4) The ease with which the system may be adapted to automatic combustion control.

(5) The successful experience with two 300-hp. units of this type installed at State Line Power Station.

BASIS OF COMPARING THE NEW SYSTEM WITH OTHER SYSTEMS

Various types of motors have been used for driving

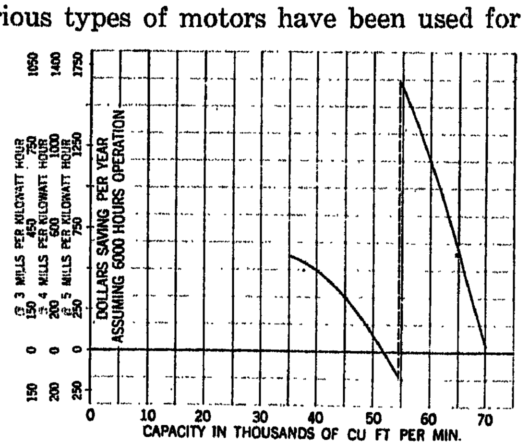

FIG. 6—ANNUAL SAVING FOR STANDARD FORCED DRAFT FAN

forced and induced draft fans. The motors most commonly used are of the induction type, in both squirrel-cage and slip-ring forms. As the draft fans on the boilers previously installed at Powerton are driven

by two-speed squirrel-cage type induction motors, the comparisons in this paper are made between the new system and that system.

Comparisons of the two systems are based on the installation of two 105,000-kw. turbo-generator units designated units No. 3 and No. 4 respectively, which are now being installed at Powerton. Steam for each

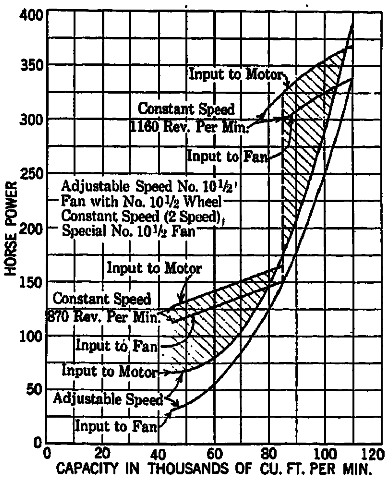

FIG. 7—COMPARATIVE PERFORMANCE CURVES FOR INDUCED DRAFT FAN

unit is furnished by two boilers of standard type and one boiler of the reheat type. The load curve for units No. 3 and No. 4 is assumed to have the same shape as the load curve for present units No. 1 and No. 2 (each rated 52,500 kw.) but increased in direct proportion to the increase in generating capacity.

ENERGY SAVING OF THE NEW SYSTEM AT POWERTON

An analysis of the application of this system to the fans of the six new Powerton boilers shows a distinct

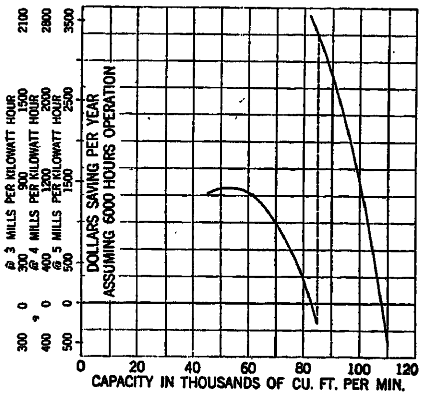

FIG. 8—ANNUAL SAVING FOR STANDARD BOILER INDUCED DRAFT FAN

saving in energy consumption. Fig. 5 shows the horsepower input to each fan and the horsepower input to each motor at various fan capacities for the two different systems of driving the forced draft fans. Fig. 6 shows for a standard boiler the saving in dollars of the new system over the old at various fan capacities based on operating 6,000 hr. per year.

Similar curves for the induced draft fan are shown in Figs. 7 and 8.

Figs. 9 and 10 show for the forced and induced draft fans respectively of a reheat boiler the saving in dollars of the new system over the old, based on operating 8,000 hr. per year.

From these curves are computed the following annual savings in dollars of the new drive over the old for the fans of four standard boilers and two reheat boilers, based on three different unit costs of energy:

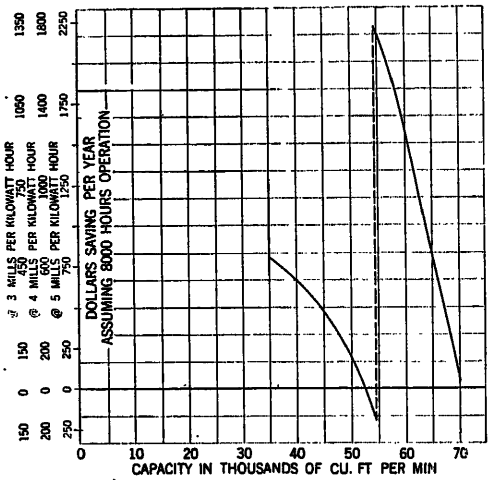

FIG. 9—ANNUAL SAVING FOR REHEAT BOILER FORCED DRAFT FAN

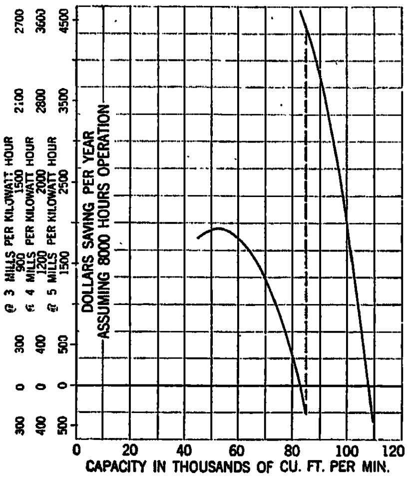

FIG. 10—ANNUAL SAVING FOR REHEAT BOILER INDUCED DRAFT FAN

	Energy cost per kw-hr. 3 Mills	4 Mills	5 Mills
Annual saving for 12 forced draft fans................	$ 4,535	$ 6,047	$ 7,559
Annual saving for 12 induced draft fans................	8,780	11,707	14,634
Total saving for six boilers.	$13,315	$17,754	$22,193

The detailed analysis of these figures is given in Table IV.

TABLE IV

ESTIMATED ENERGY SAVINGS OF NEW SYSTEM OF FAN DRIVE OVER TWO-SPEED INDUCTION MOTOR DRIVES FOR BOILER DRAFT FANS OF POWERTON UNITS 3 AND 4

Savings are figured at 3 mills, 4 mills and 5 mills, per kw-hr. respectively. Detail figures used in the following table are based on 3 mills.

Turbine and boiler loads are based on average daily load curves of Units No. 1 and 2 pro-rated for the increased capacity

	The 24-hr. load is divided into 3 periods, as follows:		
Units No. 3 and 4:			
Hr. per day............Hr.	11	8	5
Turbine load (2 turbines) Kw.	210,000	108,000	150,000
Steam requirements. ...lb./hr.	1,910,000	980,000	1,350,000
No. of boilers in operation......	6	4	6
Steam from ea. reheat blr. lb./hr.	290,000	150,000	210,000
Steam from ea. std. blr. ..lb./hr.	330,000	340,000	233,000
	Fan outputs and savings:		
Std. boiler forced draft fan:			
Cu. ft./min. of air per fan.......	46,500	48,000	33,000
Annual saving per fan in each daily period.......$	78	43	76
Annual saving all fans in each daily period.......$	605*	170†	610*
Total annual saving all fans..................$1,385			
Std. boiler induced draft fan:			
Cu. ft./min. of gas per fan.......	79,000	82,000	56,000
Annual saving per fan in each daily period.......$	90	35	175
Annual saving all fans in each daily period.......$	720*	140†	1,400*
Total annual saving all fans..................$2,260			
Reheat boiler forced draft fan:			
Cu. ft./min. of air per fan.......	56,000	35,000	44,000
Annual saving per fan in each daily period.......$	565	160	63
Annual saving all fans in each daily period......$	2,260†	640†	250†
Total annual saving all fans..................$3,150			
Reheat boiler induced draft fan:			
Cu. ft./min. of gas per fan......	89,000	55,000	70,000
Annual saving per fan in each daily period.......$	1,080	385	165
Annual saving all fans in each daily period.......$	4,320†	1,540†	660†
Total annual saving all fans..................$6,520			
Grand total annual saving all fans of units No. 3 and 4—			
@ 3 Mills per kw-hr..$13,315			
@ 4 Mills per kw-hr.. 17,754			
@ 5 Mills per kw-hr.. 22,193			

*Indicates 8 fans in service.
†Indicates 4 fans in service.

Cost of the New System at Powerton

Energy savings of this magnitude usually call for a considerable additional capital expenditure. In this instance, such is not the case. Estimates show that the savings in miscellaneous accessory equipment required by the old system but not by the new nearly offset the higher cost of the drive units and motor-generator sets of the new system.

A detailed analysis of the estimated costs is given in Table V.

TABLE V

ESTIMATED COST PER BOILER OF FAN DRIVE AND DRAFT CONTROL EQUIPMENTS FOR THREE DIFFERENT SYSTEMS FOR POWERTON UNITS 3 AND 4

	Existing systems		New system
	Damper system (2-speed motors)	Inlet vane system (2-speed motors)	Adjustable speed drive*
Fan motors:			
2—Induced draft fan motors	$ 5,500	$ 5,500	$13,400
2—Forced draft fan motors.	3,300	3,300	8,300
—Supports and enclosures.	..	..	400
—Installation............	800	800	2,000
—Circuit breakers and control, installed.........	5,000	5,000	6,650
1—Exciter motor generator set..................	..	..	550
—Speed selector switches for four fans..........	6,000	6,000	..
—Installation............	1,100	1,100	..
—Power and control cable and conduit, installed.	2,000	2,000	3,000
	$23,700	$23,700	$34,300
Vanes and dampers:			
2—Sets vanes or dampers with mech. (ind. dft.).	$ 600	$ 2,000	$ 600
2—Sets vanes or dampers with mech. (fcd. dft.).	600	1,300	600
—Installation............	300	1,050	300
2—Damper drive units......	4,250	2,400	..
—Installation............	360	360	..
—Cable and conduit, inst..	2,000	2,000	..
	$ 8,110	$ 9,110	$ 1,500
Fan speed change accessories:			
4—Centrifugal relay switch equipments..........	$ 425	$ 425	..
2—Centrifugal relay switch equip. (for interlock)..	215	215	..
—Installation............	760	760	..
—Wire and cable, inst......	800	800	..
	$ 2,200	$ 2,200	
Total cost per boiler........	$34,010	$35,010	$35,800

*Based on machine ratings given in Table II.

Other Installations

This system of driving forced and induced draft fans is also being installed in two other power stations, *viz:* the Philo Power Station of the Ohio Power Company, and the Sheboygan Power Station of the Wisconsin Power and Light Company.

The bearing construction of the a-c. motors of the Sheboygan units will be similar to those for Powerton but the design of the Philo units differs somewhat in that the frame is supported directly on the rotor shaft through anti-friction bearings, and the motor shaft, which thus carries the weight of both rotor and frame, is supported on pedestal type bearings. The method of supporting the collector rings and of housing the rings and brush rigging is similar to that used on the Powerton machines.

An analysis was made of the problem of driving a centrifugal boiler feed pump by the new system compared with using induction motors of both squirrel-cage and slip-ring types. For the motors of the adjustable speed type, the speed range was assumed to be 100 to 85 per cent. The analysis gave the following results:

While the investment costs of the slip-ring and squirrel-cage motor drives were both lower than the

cost of the new system, the total annual cost, which includes both investment and operating costs, favors the new system. It was therefore decided to install this system of drive on one boiler feed pump at Sheboygan.

The brief summary of data relating to these units is given below:

PHILO POWER STATION
(Two Pulverized Fuel Boilers)

	Forced draft fans	Induced draft fans
Number of fans	4	2
Number of drive units	2	2
Maximum fan speed	1340-r. p. m.	1005-r. p. m.
Minimum fan speed	670-r. p. m.	502-r. p. m.
Range of fan speed	100% to 50%	100% to 50%
Constant speed component (a-c. power) at maximum fan speed	244-hp. @ 1160-r. p.m.	648-hp. @ 870-r. p. m.
Adjustable speed component (d-c. power) at maximum fan speed	38-hp. @ 180-r. p. m.	100-hp. @ 135-r. p. m.
Total power at maximum fan speed	282-hp. @ 1340 r. p. m.	748-hp. @ 1005-r. p. m.
Speed of d-c. machine at maximum fan speed	Plus 568-r. p. m.	Plus 340-r. p. m.
Speed of d-c. machine (operating as a generator) at minimum fan speed	Minus 1704-r. p. m.	Minus 1020-r. p. m.
Ratio of ratings d-c. machine/a-c. motor	13.5/86.5	13.5/86.5
Number of speed regulating motor-generator sets	2	2
Rating of each speed regulating motor generator set	30-kw.	85-kw.

Total rating of all drive units .... 2160-hp.
Total rating of all speed regulating motor-generator sets ... 230-kw.

SHEBOYGAN POWER STATION
(Two Pulverized Fuel Boilers)

	Forced draft fans	Induced draft fans	Boiler feed pump
Number of drive units	2	2	1
Maximum load speed-r. p. m.	1360	1005	1880
Minimum load speed-r. p. m.	680	502	1692
Range of load speed	100% to 50%	100% to 50%	100% to 90%
Constant speed component (a-c. power) at maximum load speed	157-hp. @ 1165-r. p. m.	339-hp. @ 870-r. p. m.	605-hp. @ 1770-r. p. m.
Adjustable speed component (d-c. power) at maximum load speed	26-hp. @ 195-r. p. m.	52-hp. @ 135-r. p. m.	45-hp. @ 110-r. p. m.
Total power at maximum load speed	183-hp. @ 1360-r. p. m.	391-hp. @ 1005-r. p. m.	650-hp. @ 1880-r. p. m.
Speed of d-c. machine at maximum load speed	Plus 500-r. p. m.	Plus 400-r. p. m.	Plus 535-r. p. m.
Speed of d-c. machine (operating as a generator) at minimum load speed	Minus 1500-r. p. m.	Minus 1200-r. p. m.	Minus 535-r. p. m.
Ratio of ratings d-c. machine/a-c. motor	14.2/85.8	13.3/86.7	6.9/93.1
Number of speed regulating motor generator sets	2	2	1
Rating of each speed regulating motor generator set	30-kw.	50-kw.	40-kw.

Total rating of all drive units .... 1798-hp.
Total rating of all speed regulating motor generator sets .... 200-kw.

The a-c. motors are designed to operate at 2,200 volts three-phase.

Another application of this system to the driving of power station auxiliaries differs radically from the ones previously described and it illustrates the versatility of the system. It consists of a 2,500-hp. drive unit geared to a reciprocating pump which delivers boiler feed water under a pressure of 1,500-lb. per sq. in. This application calls for constant torque at adjustable speed. The design of the drive unit differs from the Powerton fan drive units in that the armature

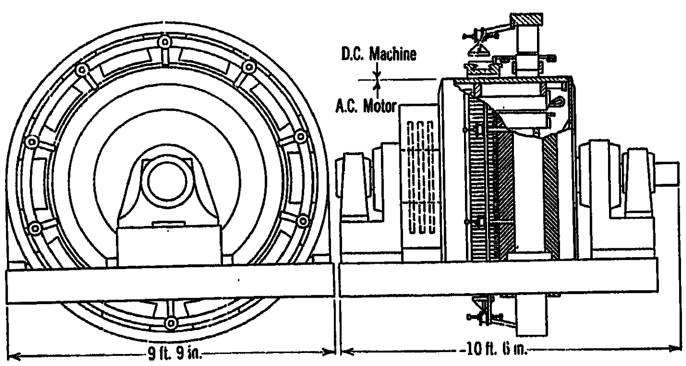

Fig. 11—2,500-Hp. Drive Unit

of the d-c. machine is assembled on the frame of the a-c. motor. The d-c. machine is thus concentric with the a-c. motor. The outline and dimensions of this drive unit are shown in Fig. 11. Two machines of this type are now under construction. The principal data pertaining to this application are given in the following table:

Max. shaft speed	708 rev. per min.
Min. shaft speed	282 rev. per min.
Range of shaft speed	100 to 40 per cent
Constant-speed component (a-c. power) at max. shaft speed	1750 hp. @ 495 rev. per min.
Adjustable speed component (d-c. power) at max. shaft speed	750 hp. @ 213 rev. per min.
Total power at max. shaft speed	2500 hp. @ 708 rev. per min.
Ratio of ratings—d-c. machine/a-c. motor	30/70
Rating of speed regulating motor-generator set for each drive unit	750 kw.
Over-all efficiency of drive unit and motor-generator set—	
At maximum speed	88.4 per cent
At middle speed	88.6 per cent
At minimum speed	78.3 per cent

The a-c. motors are designed for 2,200 volts, three phase.

Automatic Combustion Control

Present systems of automatic combustion control are complicated because of the complications of the draft control. In a system which employs two-speed squirrel cage motors for driving the fans a change in load which necessitates a change in motor speeds calls for a switching operation, the operation of dampers both before and after the switching operation and, when dropping from the higher to the lower speed, the proper timing of the switching operation to prevent undue mechanical stresses on the equipment. All of these operations must necessarily be controlled by the automatic combustion control system.

A new and simple system of automatic combustion control has been developed to take advantage of the simplified new system of fan control. The combustion control functions by simultaneously increasing or decreasing, in the proper ratio, the speeds of the forced draft fans, the induced draft fans, and in the case of pulverized fuel plants, the coal feeders, to meet a change in the demand for steam. While these adjustments are being made on the group as a whole to regulate for steam demand, secondary adjustments are made simultaneously on the individual controls to maintain the proper furnace pressure and the proper ratio of air to fuel. Three pilot motor-operated field rheostats make all the necessary adjustments on each boiler. Each fan control rheostat is driven by two pilot motors through a differential gear. One motor is controlled by the master pressure gage, while the other is controlled by either a furnace pressure gage or a fuel/air ratio control. These secondary corrections are superimposed on the master control adjustments through the differential gears.

This brief description gives some idea of the possibilities for simplification of the automatic combustion control equipment. A complete description of the system would be too long to include in this paper. A wiring diagram which shows the functioning of the principal control elements is given in Fig. 12.

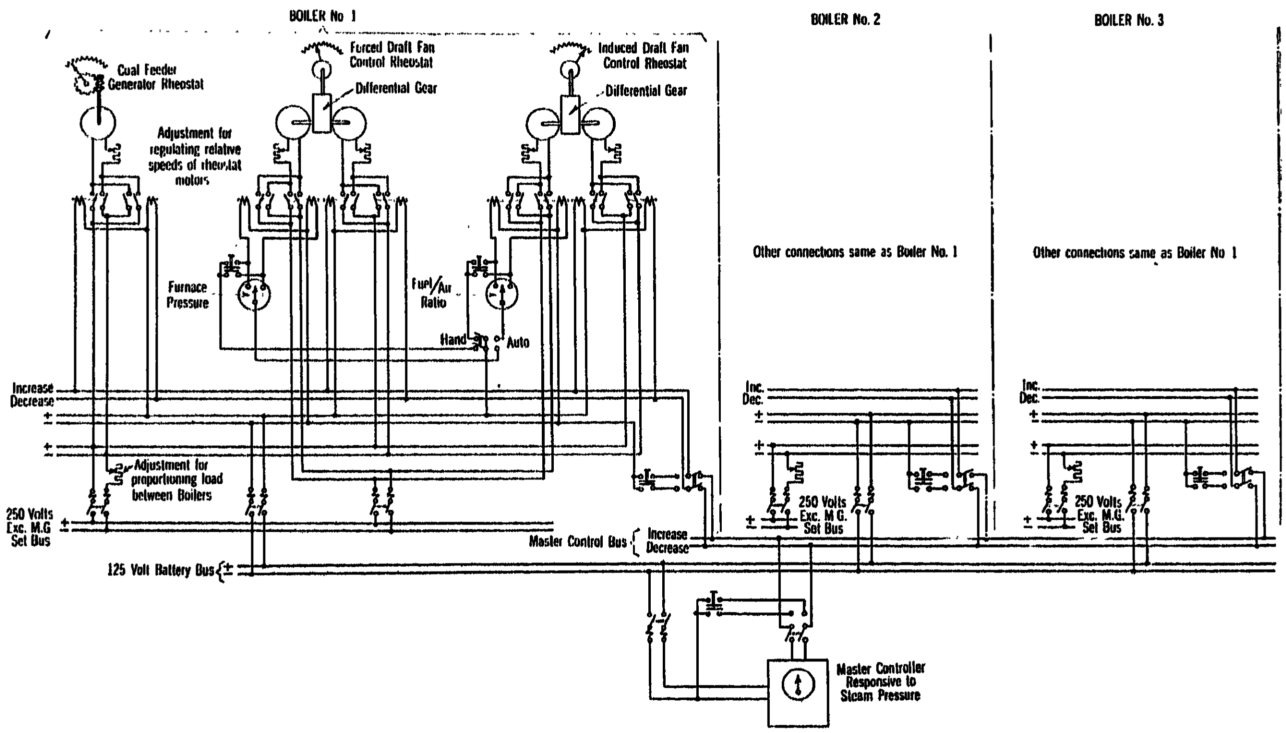

Fig. 12—Wiring Diagram of Simplified System of Automatic Combustion Control

Acknowledgment

In conclusion, the author wishes to acknowledge his indebtedness to Mr. R. B. Williamson of the Allis-Chalmers Manufacturing Company for the interest he has shown in this system through the various stages of its development and for the assistance he has rendered in bringing it to its present stage of development.

Discussion

Fraser Jeffrey: To derive any benefit such as a gain in efficiency from a variable speed drive as the system described by Mr. Rossman, or a Ward Leonard system, or the Scherbius system, etc., it is necessary to operate at reduced speeds for reasonable lengths of time otherwise a regular single-speed slip-ring motor operating at, or nearly at its full speed will be more efficient than any of those multi-unit variable speed systems. Therefore, the necessity for adjustable speed is of prime importance before the selection of the apparatus can be intelligently made.

We might think of the drive just described as being essentially a constant torque drive best suited for operating loads of this nature but it can also be advantageously used for variable torque drives such as fans or centrifugal pumps. It has the further advantage of maintaining constant speed regardless of load and with this characteristic should find a much wider field of application than it has up to the present time. It is not necessarily confined to equipment of relatively small capacity and it is of interest to note that units of this type are now being built which have a rating of 2,500 hp. with a two and one-half to one speed range on a constant torque load. The capacity and speed range desired, dictates largely whether the armature of the d-c. machine should be rigidly connected to the revolving stator of the a-c. machine, or flexibly connected to it by means of texropes capable of operating on short centers at a fairly large speed reduction thus allowing the use of a standard d-c. machine.

Outside of the fact that the Rossman system is highly efficient over its entire speed range because the converted power is only that relatively small amount represented by the speed range and not the entire power, the use of practically standard types of machines for the auxiliaries and, with the exception of mechani-

cal features, the same for the a-c. machine of the main drive units, tends toward simplicity, low maintenance costs and the use of apparatus with which the operating engineer is most familiar.

The Rossman system has some points pertaining especially to the relationship of power requirements with respect to speed range and kind of load that are interesting.

While the relative capacities of the d-c. machine and the induction motor of the drive unit are computed from a socalled "base speed," which is the full load speed of the induction motor, theoretically the size of these machines will always remain unchanged regardless of what the base speed is in its relationship to the limits of the speed range desired, provided the power required at the high speed remains the same. For instance, assume a constant torque condition of load requiring 600 hp. at a maximum speed of 720 rev. per min., a base speed, neglecting slip of 600 rev. per min. and, that a speed range of 120 rev. per min. plus or minus is required. Then for either the maximum speed of 720 rev. per min. or, the minimum speed of 480 rev. per min., the d-c. machine would have to be capable of delivering 100 hp. at a speed of plus or minus 120 rev. per min. if the armature were direct coupled to the revolving stator of the induction motor which would be rated 500 hp. at 600 rev. per min.

If a lower speed than 480 rev. per min., say 360 rev. per min. were required, then by using the same drive as above, the size of the induction motor would remain unchanged, but, the d-c. machine would have to be capable of delivering 200 hp. at minus 240 rev. per min., or, twice the power at twice the speed as before, or, a machine of the same theoretical physical size, except that the commutator would have to be able to handle twice the current at twice the speed as before.

Taking any other number of speed conditions, it will be found that the theoretical horsepower divided by speed, or, horsepower per revolution physical sizes of the two drive machines of the main unit remain unchanged.

On the other hand, as the power or capacity of the regulating unit is the same as that of the d-c. machine of the drive unit, then it will be noted that the most economical size for both the drive unit and the regulating unit for constant torque conditions will be obtained when the base speed is half way between the maximum and minimum speeds.

For a variable torque load, however, this does not hold true, as it is then desirable to have the base speed closer to the high speed, so that the plus capacity of the d-c. machine of the drive unit will be as small as possible consistent with the mechanical limitations that might be imposed on either the induction motor stator or the d-c. machine of the drive unit when rotating negatively at maximum speed. For fairly large speed variations such as two to one, or three to one, the capacity of the d-c. machine of the drive unit might be set as some value of load approximately the same or somewhat less than that required by the fan at its lowest speed and then the size of the regulating unit will also be as small as possible. Thus, if we have a two to one variable speed, variable torque fan load requiring 600 hp. at 720 rev. per min. for the maximum speed, and if it were possible to select a base speed of 630 rev. per min., then the size of the induction motor would be 525 hp. at 630 rev. per min. The size of the d-c. machine for the high speed for 720 rev. per min. would be 75 hp. at plus 90 rev. per min., which is the exact load required (75 hp. at minus 270 rev. per min.) to drive the fan at the low speed of 360 rev. per min.

In actual practise it is necessary to adhere to "base speeds" that correspond to a particular synchronous speed, and to consider the mechanical limitations of the revolving stator of the a-c. machine and also the d-c. machine of the drive unit.

C. M. Gilt: There is no question in any one's mind that there is a large field for a more satisfactory method of obtaining speed adjustment in a-c. motors. Particularly in the larger size motors, present methods are both expensive in installation cost, and involve high losses. Where a wide range of speed control has been essential it has quite commonly been accomplished by conversion to direct current, using adjustable speed d-c. motors or even Ward Leonard control, both of which methods are expensive in cost and losses.

The method proposed by Mr. Rossman has undoubtedly a real field of application, providing, as it does, much of the flexibility of Ward Leonard control, without requiring the large d-c. motors and converting equipment.

With these advantages in view, we included this type of drive in a very intensive study comparing several electrical methods of driving the induced draft fans on the new boilers to be installed in our Hudson Avenue station, and we were disappointed to find that with our particular plant layout and load duration curves, total costs ran somewhat higher than on squirrel-cage motors with vane control or on slip-ring induction motors.

A comparison of the total costs with their various component factors is indicated in the following table:

ECONOMIC COMPARISON OF ELECTRIC DRIVES FOR SIXTEEN 1,000-HP. INDUCED DRAFT FANS

Method of draft control =	Constant-speed		Vane regulation		Adjustable speed			
Type of electric drive =	1-Speed squirrel cage 1160 rev. per min.	2-Speed squirrel cage 1160/580 rev. per min.	2-Speed squirrel cage 1160/870 rev. per min.	3-Speed squirrel cage 1160/870/580 rev. per min.	19-Point wound rotor 1160–400 rev. per min.	1-Range Rossman drive 1340–670 rev. per min.	2-Range Rossman drive 1005–100 rev. per min.	Ward Leonard drive 870–50 rev. per min.
Electrical installation	23.9	28.0	27.5	30.8	41.5	49.5	57.6	84.0
Regulating damper installation						0.5		
Vane installation	2.6	2.6	2.6	2.6				
Space evaluation	2.3	3.1	2.8	3.9	5.5	4.3	5.4	4.1
Capacity charge	47.5	47.7	43.2	43.1	51.3	44.7	43.7	61.5
Energy charge*	23.3	10.2	14.2	9.9	17.6	14.6	8.4	26.5
Electrical maintenance*	1.2	1.5	1.4	1.7	2.7	6.9	7.5	4.2
Fan maintenance*	9.6	9.6	9.6	5.9	5.4	5.4	4.7	4.7
Vane maintenance*	3.2	3.3	3.3	2.1				
Total	113.6	106.0	104.6	100.0	124.0	125.9	127.3	185.0

*Capitalized on the basis of a 12½ per cent carrying charge.

This study was based upon sixteen 1000-hp. driving units each of which in the case of the Rossman drive consisted of an 850-hp. squirrel-cage a-c. motor and an 150-hp. d-c. adjustable speed motor. Two methods of obtaining draft control at speeds less than 50 per cent were considered, first by damping, second, by using a two-speed squirrel-cage motor with the adjustable-speed d-c. motor superimposed. Previous studies on different size fans using a single-speed a-c. motor with a large enough d-c. motor to reduce the speed to 15 per cent of maximum showed a

higher cost due to the large d-c. motor and motor-generator sets required.

In our installation, expensive building changes would be required for either the slip-ring, Rossman or Ward Leonard drives. In the above tabulation, these building changes are not included but the required space is evaluated at $0.75 per cu. ft., and is found by increasing each dimension of a piece of equipment by two ft. and then doubling this volume to provide adequate space for handling.

Energy was estimated at $0.003 per kw-hr. A life of 28 years was assumed with a usage increasing during the first three years of life and then a gradually decreasing hp-hr. usage per year. The load factor and method of operation in which all boilers operate at reduced ratings rather than banking some during the daily light load periods require many hours of service at light loads, in which the total energy consumption, regardless of motor efficiency is small.

The capacity charge was based on a fan output which loaded the motors to about 75 per cent of their full load rating as it was found that the maximum demand of the station, with 10 per cent of the boilers out, would place this load on the motors, the additional capacity being installed to provide for emergency conditions of fan or boiler outage. The capacity and energy charges for the Ward Leonard control may appear surprisingly high. They may be accounted for in the low over-all efficiency of the motor-generator sets and d-c. motor drives expecially at the light loads under which these sets operate during the greater part of the time.

Installation costs include engineering, drafting, contingencies and overhead, with somewhat greater margin in engineering and drafting allowed for the Rossman drive due to lack of experience with such an installation.

The electrical maintenance charged against Rossman drive may appear high, but it was believed that the maintenance (including blowing out, cleaning inspecting, repairing, etc.) for the d-c. portion of the Rossman drive, would be more than that of a squirrel-cage motor, in addition, there is the maintenance of the motor-generator set, the high-voltage a-c. rings, switches, rope drive, etc. Fan maintenance, including fan reblading is materially lower for the adjustable speed drives due to the lower average speed with the consequent decrease in cinder wear.

In these figures, no evaluation is placed upon the intangible advantage of the smoothness and wide range of speed adjustment obtainable with either the Rossman or Ward Leonard drives, and its effect on fire conditions, a factor which cannot be ignored when the tangible factors are close.

It is apparent from the figures in the above tabulation that the capacity charges for the squirrel-cage motors and the Rossman drive are approximately equal, and while there is some saving in energy for the Rossman drive over any of the other methods, this saving is not great enough to offset the higher installation costs.

It is quite evident, however, that with a load duration curve such as would apply if the load factor on the station were considerably better, the energy item would assume such proportions as to throw the balance of over-all cost in favor of the Rossman drive.

R. R. Sheely: The fact that Mr. Rossman uses the d-c. regulating machine as a motor through part of the speed range and as a generator through the remainder of the speed range permits the use of a comparatively small d-c. machine. This also accounts for the comparatively high efficiency of the scheme as compared to adjustable speed drives such as the Kramer or Ward Leonard systems since the major portion of the energy is transferred directly from the a-c. bus to the mechanical load by means of the special a-c. motor.

The special a-c. machine is the most undesirable unit of the system. Slip rings operating continuously at voltages commonly used for power house auxiliaries will require frequent inspection and cleaning or trouble will be sure to result. The development charges will also be high since practically every installation will be sufficiently different from previous jobs to prevent the use of duplicate parts. It appears, however, that the advantages to be gained from the simplified combustion control system when using this type of drive will overbalance the disadvantages of the introduction of complicated electrical machines.

R. A. Hentz: The author stated that the motor-generator set under certain conditions acts as a motor and in other cases as a generator. Can this motor be either synchronous or induction and what is usually used? I presume, as a stator is excited from the source of supply, an induction motor could be used to operate as an induction generator when delivering power back to the system.

A. M. Rossman: Answering Mr. Hentz' question,—the a-c. machine of the motor-generator set or the a-c. motor in the case of the drive unit may be of either the synchronous or the induction type. In the equipments that have been purchased up to date the a-c. machines have all been of the induction type. When delivering electrical energy the induction motor receives excitation from the source of supply and functions as an induction generator. Some of our more recent studies, involving large sized units, are based on a-c. machines of the synchronous type.

Transformers with Load Ratio Control

BY ARTHUR PALME[1]

Member, A. I. E. E.

Synopsis.—Voltage regulation on transformers under sustained load has made rapid strides in the last eight years and found very wide application in extended power systems and on industrial loads. Originally it was found economical to equip only very large transformers for load ratio control, using apparatus designed for high currents.

This paper describes, and compares with earlier developments, a novel equipment of low current rating, that has been devised especially to control small blocks of power, thereby greatly widening the economic field of application of load ratio control. The electro-mechanical features of this equipment are stressed particularly.

* * * * *

FROM a small beginning in 1923, changing of ratio on transformers under load, or "load ratio control," developed rapidly until it has now become quite indispensable, without which many a modern transmission system and network would be under a decided handicap. Reducing the amount of reactive kv-a. flowing between power stations, it increases the efficiency and the maximum output of systems; it allows a flexible tie-in between systems; and it finally offers a simple and economic method of regulating voltage for industrial loads.

There have been numerous publications on this subject, and it is assumed that the reader is already familiar with the modern practise of designing a transformer winding with taps, so arranged as to permit changing ratio under sustained load. Classified according to basic principle, the following three methods are being used today:

1. A single winding with a tap for each voltage, two selector switches and two current interrupting devices. (See diagram 1A of Fig. 1).
2. A single winding with N taps for $(2N-1)$ operating positions, two selector switches and two current interrupting devices. (See diagram 1B of Fig. 1).
3. A single winding with N taps for $(2N-1)$ operating positions, with a current interrupting device for each tap. (See diagram 1C of Fig. 1).

Method (1) will give uniform steps in ratio under all conditions of load and power factor. Since the reactor is short-circuited on all operating positions, it does not increase the no-load loss on any ratio, nor does it add any reactive kv-a. to the system.

Method (2) has additional no-load losses and reactive kv-a. on alternate positions, and requires a reactor twice the size of the one needed for Method (1) which introduces an appreciable transient drop in voltage during the process of changing taps.

Method (3) also gives additional no-load losses and reactive kv-a. on alternate positions, and furthermore gives incorrect or unequal ratio steps when loaded at less than unity power factor. This inequality of steps makes it necessary, therefore, to provide a greater number of steps than for Method (1) for a specified voltage range.

The shortcomings of Method (3) can be alleviated by providing an additional current interrupting device, which short-circuits the reactor on alternate operating positions.

The advantages of Method (1), explained above, plus the fact that it lends itself readily to the standardization of parts for use on a variety of ratings, were the deciding factors leading to the development of the apparatus herein described.

During the past few years the rapid growth in the

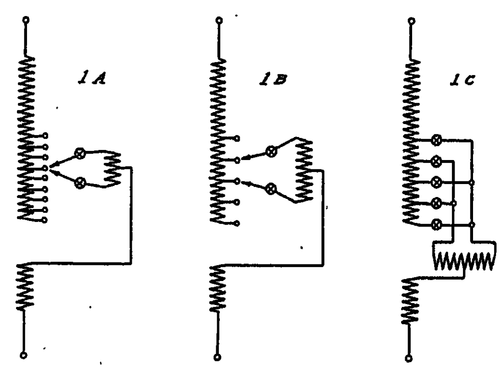

FIG. 1—THREE METHODS OF LOAD RATIO CONTROL, EACH FOR NINE VOLTAGES

number of load ratio control transformers has enabled the designer to obtain valuable operating experience and to formulate exact requirements for the essential parts of these equipments.

The cost of the necessary electrical and mechanical accessories to permit changing of taps under load, is an appreciable percentage of the over-all cost of the transformer. With a given and standardized mechanical equipment, the cost of the load ratio control apparatus proper does not change materially with the amount of power it has to handle. This means that the smaller the kv-a. rating of the machine to which it is applied, its cost in per cent of that of the whole transformer will obviously be higher. Considering, however, the many operating advantages

1. General Transformer Engg. Dept., General Electric Company, Pittsfield, Mass.

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which the installation of such a machine affords, this increase seems sound and justified, provided the output of the transformer is not too small. Experience and past demand indicated that the majority of transformers which were equipped with load ratio control were of such size that the current to be handled by the selector switches and interrupting device was between 500 and 1,000 amperes. Consequently, a line of apparatus was developed suitable for this range of current and for circuit voltages ranging from 15 kv. to 73 kv.

The wide use of load ratio control transformers in this country can perhaps best be appreciated when it is realized that the total regulated transformer capacity now installed is more than five million kv-a. It was perhaps a happy coincidence that load ratio control was developed just about the time that the use of long transmission systems, networks, and tie-ins began to spread rapidly over the country.

Having thus established a firm foundation for

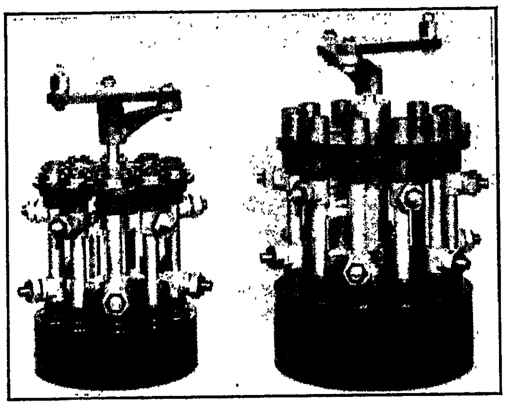

FIG. 2—RATIO ADJUSTERS UP TO 1,000 AMPERES FOR 9 AND 11 POSITIONS, RESPECTIVELY

heavy current apparatus, the demand for a similar equipment, suitable for much smaller currents, and therefore smaller in size and lower in cost, became acute. With a load ratio control apparatus of such a type, the cost per cent of the switching equipment for relatively small transformers can be maintained at about the same economically sound ratio as for large units.

Following this plausible route of reasoning, the existing heavy current type of load ratio control equipment has recently been augmented by a new line of apparatus for voltages up to 15,000 volts and currents not in excess of 400 amperes. Experience in the field, covering a period of several years with the heavy current equipment, justified the use of the same method of operation for the small type. In other words, diagram 1A of Fig. 1 applies unchanged to either of the two types; the difference being entirely in the mechanical construction. A short description will best serve to illustrate the differences.

A. HEAVY CURRENT TYPE

For current ratings up to 1,000 amperes, the multipoint selector switch, or ratio adjuster is a very substantially built device consisting of two molded compound heads, into which are fastened securely 10 or 12 round copper rods. (See Fig. 2.) To insure additional electric strength between adjacent rods, a short collar of "herkolite" surrounds each rod where it goes through the top and bottom head. In the center of this cage-like structure moves a set of copper contact fingers, each under the pressure of a strong helical compression spring. A combination of crankshaft and cam arrangement causes this set of fingers to slide on and off each rod as the center shaft is revolved, but maintaining at the same time permanent contact with the center which is connected to one of the 10 or 12 rods. To 9 or 11 of these rods are carried cables of suitable size from the taps in the transformer winding. The wiping action of the fingers on each rod immediately before making final contact, and the mechanical sturdiness of the whole adjuster (the 10-point type weighs 82 lb., the 12-point type weighs 116 lb.) are important features of these switches. Operating always under oil, the lubricating problem is easily solved. Mechanical life tests on these adjusters showed no visible wear after half a million operations.

For a single-phase transformer two of these adjusters are required; for a three-phase transformer two three-phase stacks are necessary. According to the cycle of operation, provision must be made to operate these adjusters intermittently, that is, on a single-phase transformer one of them has to be reset at a time. On a three-phase transformer one three-phase stack must be reset at a time. This is accomplished by a specially designed *intermittent gear*, consisting essentially of a gear sector which when turned, engages alternately with a small pinion at the right and one at the left; the two pinions transmitting their motion to the operating shafts of the ratio adjusters. Gear and adjusters are mounted as a rule, inside the transformer tank and form a self-contained unit with core and coils as shown for a single-phase example in Fig. 3, with the main driving shaft brought out oil-tightly through the wall of the transformer tank.

Consistent with a maximum current rating of 1,000 amperes, a heavy duty current interrupting device is fastened to the outside of the transformer tank. A special type of *oil-immersed contactor* was developed for this purpose. The very high kv-a. rupturing capacity to which modern circuit-breaker designers justly point with pride, is not required for the duty imposed upon breakers in circuits as in Fig. 1. Current carrying ability, good insulation to ground, short-circuit strength and long mechanical life are of sole importance. Life tests have indicated that for very frequent operation such as encountered in load ratio control, as compared with the only occasional opening of a circuit breaker on

a line, a much longer life of arcing contacts results if they separate horizontally forward rather than downward, because the arc has less chance to burn the contacts.

These considerations have led to the design of a single break, forward motion, double contact type of

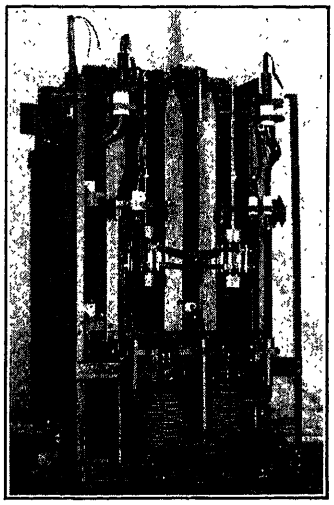

FIG. 3—CORE AND COILS FOR SINGLE-PHASE TRANSFORMER, EQUIPPED FOR LOAD RATIO CONTROL

Transformer rated 12,500/18,750 kv-a., 69,000 to 13,800 volts, with load ratio control of the 73-kv. type in the high-voltage winding

contactor; one pair of contacts to carry the current under normal operation, and one pair of arcing contacts. The contactor unit is mounted on two heavy type petticoated porcelain through-bushings, which

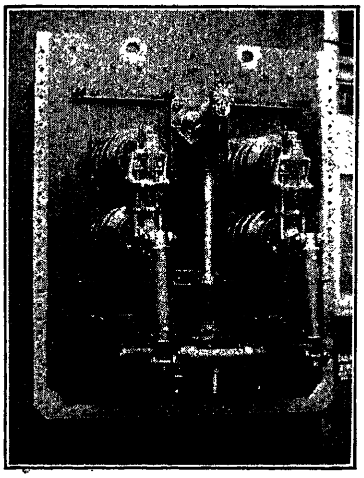

FIG. 4—SINGLE-PHASE CONTACTOR PANEL FOR 37-KV. CIRCUIT AND UP TO 1,000 AMPERES

Oil tank removed

are bolted to a thick steel plate. (See Fig. 4.) For single-phase transformers such a steel panel carries two contactors; for a three-phase machine, six contactors. A scroll cam and two steel rollers moving in its groove, together with two sets of toggle levers, translate the rotating motion of a vertical drive shaft into intermittent opening and closing of the contactors. While the steepness of the groove in the scroll cam determines the *closing* speed of the contactors, their *opening* is made trip-free and very fast by the roller upsetting the toggle. The whole arrangement is mechanically very simple. Depending upon the circuit voltage, these contactors can be mounted on porcelain bushings for 15-, 37-or 73-kv. operating voltage. Contactors of this type are capable of rupturing 1,000 amperes at least 7,500 times with one pair of arcing tips, representing an average useful life of over two years, at the end of which time the two pairs of tips per phase can be readily and cheaply renewed. Enclosing the contactors and bolted oil-tightly against the main steel panel, is an oil tank. For the three-phase type, insulating flash barriers are placed between phases.

For the remote operation of these mechanisms is provided a powerful—

Motor Drive, located underneath the contactor

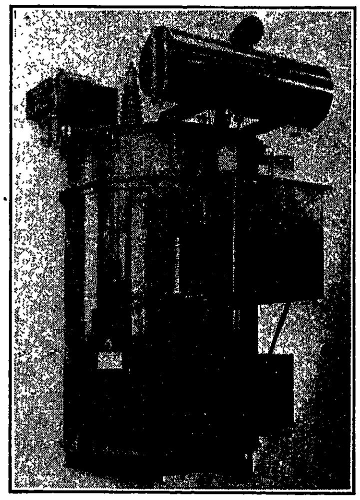

FIG. 5—EXTERNAL VIEW OF SINGLE-PHASE TRANSFORMER WITH LOAD RATIO CONTROL

Transformer rated 20,000 kv-a., 132,000 grounded Y to 22,000 volts

tank. On transformers in short tanks, the drive is directly underneath, while on tall tanks the drive is lowered near the trucks so as to be conveniently accessible for inspection or emergency hand operation. In addition to the customary accessories such as a motor reversing relay, a positioning controller, a limit switch, a dial for local and remote position indication, etc., the drive also contains an automatically operated clutch which disengages the motor if an attempt should be made to run it beyond limiting positions. Worthy of note also, is the introduction of electrodynamic braking of the motor, which insures prompt stopping without the necessary maintenance of brake bands. A weatherproof and dustproof housing encloses the motor drive.

Fig. 5 shows the external appearance of a complete, heavy current type load ratio control transformer. This is one unit of a 60,000-kv-a. three-phase bank.

rated 132,000 volts grounded Y to 22,000 volts, with control at the neutral of the 132-kv. windings. Nine operating positions are provided between the no-load ratio limits of 116,000 and 148,000 volts.

B. Low-Current Type

The main difference between the heavy-current type and the new equipment for lower current and voltage lies in the simplified type of selector switches (ratio adjusters) in a smaller type of oil-immersed contactors, and a smaller motor drive.

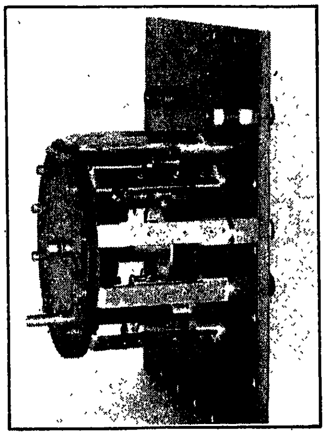

Fig. 6—Twin Ratio Adjuster for Nine Operating Positions and up to 400 Amperes

1. Ratio Adjusters. To comply with the diagram 1A of Fig. 1, two ratio adjusters or selector switches are required, the individual points of which are connected to one set of transformer taps. To insure the proper mechanical sequence of operation, provision has to be made to move these two sets of switches one at a time. In the large type of apparatus an intermittent gear is used to accomplish this. In the smaller sizes it has been found possible to combine two ratio adjusters and the intermittent gear into one piece of apparatus called "twin ratio adjuster." (See Fig. 6.) The construction comprises essentially two dial type switches, each operated by a Geneva stop gear and a driving pawl. When turning the main driving shaft one complete revolution, each dial switch will be moved a definite angular distance from one tap contact to the next.

Formerly known dial switches were either of the solid contact and movable brush type, or of the stationary clip and moving rigid knife type. Both of these constructions, even when made very accurately, are difficult to maintain in perfect contacting condition. The new dial switches have stationary knife contacts and movable but *self-alining* clip contacts. Pressure on the clips is maintained by reliable helical compression springs. The stationary contacts are copper bars to which are welded suitably located copper blades. Nine of these copper bars are held in a cage-like fashion between two heavy compound end-plates. The moving clip contacts are attached to two molded compound Geneva gears, each with nine scallops, corresponding to the nine fixed contact bars.

A twin ratio adjuster of this type represents therefore, a very compact unit, giving the two sets of contact fingers and the desired intermittent motion in a mechanically simple way. The wiping nature of the contact assures excellent current carrying ability, which further improves with use. Electro-dynamic stresses in case of a short circuit are entirely eliminated, since the contact clip grips the stationary blade from both sides. Tests with over 25 times normal current (more than 10,000 amperes) showed neither welding nor sputtering. One such unit is required for a single-phase transformer; three of them for a three-phase machine. In the latter case, the three twins are gang-mounted in a straight line, with insulating couplings between them. It is customary to use the rear plate of the twin adjuster as an oil-tight window, fitting over an opening in the upper part of the transformer tank so that the adjuster is mounted outside of the main tank in its own oil tank.

2. Contactors. The current carrying and current interrupting duty of these new, smaller equipments, being limited to 400 amperes, makes it possible to simplify the design of the contactors. (See Fig. 7.) A great many laboratory tests were made, to investigate the possibility of carrying and arcing on the same pair of contacts, with very satisfactory results. Even at double the rated current (800 amperes) thermo-couples fastened to well-worn tips, recorded after several hours no undue temperature rise of the contacts. Consequently, the new light-duty contactor was made with only a single pair of contacts per pole.

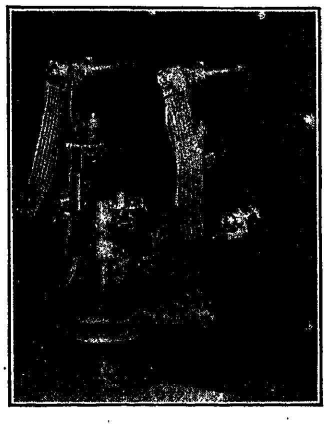

Fig. 7—Single-Phase Contactor up to 400 Amperes

Removed from oil tank

Further research indicated that the position of the contacts has a decided influence on the life of the arcing tips, as explained for the heavy current type. Therefore, the design of these contactors is also made so as to open forward in a nearly horizontal plane. A further simplification was made possible by mounting the con-

tactors on an insulating panel, without the use of porcelains, and by using insulating arms on the contactors.

A circular metal scroll cam, located between the two contactors, accomplishes enforced opening and closing of the two contactors in proper and definite time

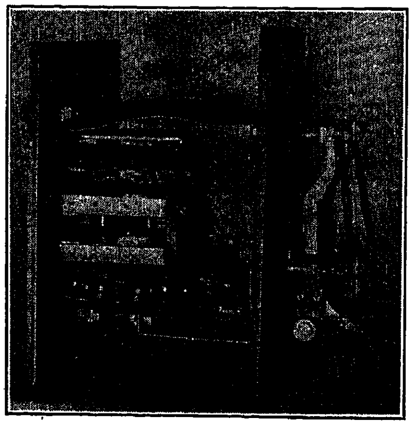

FIG. 8—ASSEMBLY OF TWIN RATIO ADJUSTER AND CONTACTOR FOR SINGLE-PHASE LOAD RATIO CONTROL

Removed from its oil tank

sequence with the twin ratio adjuster, which is driven by the same shaft.

The contactors, with their simple cam mechanism, are located in a small cubical steel tank, which contains also the twin ratio adjuster already described. The arcing of the contactors gradually carbonizes the oil, which necessitates taking two precautions:

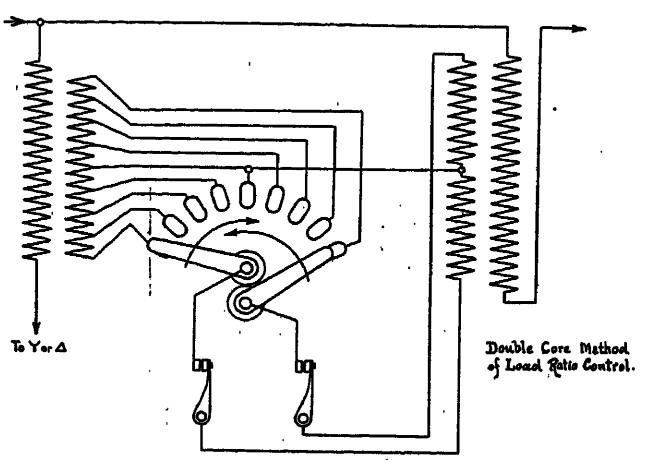

FIG. 9—SINGLE-PHASE DIAGRAM FOR DOUBLE-CORE METHOD OF LOAD RATIO CONTROL

1. All insulating surfaces are in a vertical position to prevent carbon depositions.

2. The oil in the arcing compartment is prevented from mixing with the oil in the ratio adjuster compartment.

Fig. 8 shows a view of the assembled ratio adjuster and contactor panel taken out of their oil tank.

For certain transformer connections, particularly for double-core transformation on very high-voltage regulating transformers shown in diagram Fig. 9 it becomes necessary to move the two contact arms of a twin ratio adjuster in opposite directions. This is accomplished readily by the introduction of a pair of reversing bevel gears.

3. Motor Drive. Depending upon local circumstances, various methods of remote motor control are applicable to these small load ratio control equipments. A bank of three single-phase transformers can be operated by *one* motor drive with interconnecting shafts between the three units. This results in lowest cost, great simplicity, and absolute synchronism of the three phases. Universals and slip-joints in the interconnecting shafting make misalinements in the set-up of the individual transformer units, of no consequence. It is also possible to provide each single-phase unit with its own individual motor drive, all of them connected to a common control switch, so that they all pick up together and complete their cycle of operation as governed by a controller on each unit.

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Discussion

L. F. Blume: The development of load ratio control apparatus for application to large high-voltage power transformers has been fully justified by their successful operation over a number of years, and by the increasing demand for them on large interconnected systems. The fact that in this field the inherent cost of the mechanical parts was a rather small fraction of the transformer cost warranted the development of the mechanism on the most conservative lines, in order to obtain complete assurance of reliable operation and also the best possible electrical characteristics. This point of view produced a piece of apparatus, which, on account of the inherent cost of the mechanical structure, became uneconomical for application to smaller transformer ratings.

The smaller outfit which is described in the paper under the heading of "Low Current Type," was developed primarily to meet the demand for a less expensive equipment for application to moderate size transformers. It is obvious that it would have been a step backward to obtain a less expensive outfit by sacrificing either reliability of operation or the many desirable electrical features of the larger size. Such features as the following are all valuable in the smaller as well as in the larger applications.

1. Uniform voltage steps throughout the range of control at all loads and power factors
2. Elimination of circulating current on all operating positions.
3. Minimum losses and costs obtained for current limiting reactor.
4. Flexibility in application.
5. Two multiple contacts on all operating positions.

Cost reduction was brought about without sacrificing any of the above features, by an intensive study of the mechanical design, having in mind the simplification of the mechanical structure and taking advantage of the accumulated knowledge of the performance of load ratio control in test and in the field during the last five years.

John S. Lennox: We have found that important advantages in manufacture and installation have resulted from assembling the ratio adjusters and contactors in the manner described.

Until the development of the "twin ratio adjuster" this unit assembly mounted entirely separate from the core and coils of the transformer was not practical without sacrificing the important advantages of method (1) as listed in the paper. Furthermore, it is accomplished in this design with a minimum length of tap leads, because the connections to the ratio adjuster are made on the inside of the transformer tank.

The sturdy construction, heavy contact pressures and complete mechanical interlocking that have resulted in uniformly successful operation of the heavy current equipments have been retained.

This design, which will be known as type LR-12, has proven so satisfactory in manufacture, application and operation that its use is being extended to other ratings. A 1000-ampere, 15,000-volt equipment has already been developed, only those changes being made as are required for the higher current rating.

W. W. Edson: The advantage of load ratio control soon won its adoption to many transformers, but, as so often occurs with new apparatus, mechanical defects of the equipment itself have frequently tended to discredit such installations.

A single mechanical failure may cause a disastrous electrical fault or may produce an adverse reaction against tap-changing equipment in general. An installation for which the customer is paying thousands of dollars may be marred by the use of a cheap and unreliable contactor or by attempting to use a house lighting switch as a limit-switch. Frequently the gears are fastened to a shaft by inadequate pins instead of keys, thus introducing the possibility of the equipment being left on different phases. Operating cams or other details made of insulating material may not have been properly dried and the entrapped moisture might cause an electrical fault.

Accessibility for maintenance, inspection and repairs, visibility of the operation indicator, ease in manual operation, etc., are requirements which must be given careful consideration in designing new equipment such as this.

The final inspection and tests should be made after the tap-changing equipment has been installed on the transformer to insure there has not been an unexpected lowering of the voltage rating and to prevent any possibility of the three phases being out of step with each other.

Forces in Turbine Generator Stator Windings†

BY J. F. CALVERT*

Associate A. I. E. E.

Synopsis.—Experience has shown that the forces on turbine generator armature windings during short-circuit conditions are large. The windings may be seriously damaged if adequate consideration is not given to the design of the coil bracing and support.

In this paper the forces are calculated for a particular case by the use of images, by the change of flux interlinkages, and by the $\int H^2\,d\,s$ *over some surface in air which surrounds the conductor under consideration. A new and relatively simple proof is given for the validity of the latter method. The limitations and desirable applications of each method are considered.*

Forces on conductors in armature slots are computed when saturation is considered, and when neglected. Approximate formulas are derived for the forces on coil sides within one layer of the conical end winding, and for the straight coil extensions from the slots. A numerical example is given in each of those cases. The applicability of certain of these formulas to the phase connecting rings is pointed out. The force on the entire conical surface of the end winding is discussed qualitatively.

Certain desirable features of end winding bracing are mentioned. In most of these cases, the instant considered is that following a line-to-neutral short circuit when the maximum possible instantaneous current is flowing.

* * * * *

I. General Discussion of Forces during Short Circuit

A. General Problem. It is the purpose of this paper to consider the maximum forces exerted in turbine generators on the various parts of diamond coil stator windings. Conditions at the instant when the maximum possible instantaneous current flows in the armature winding on a line-to-neutral short circuit are given the most attention. A great deal of work has been done by previous investigators to establish methods for pre-determining the magnitudes of the currents, which result from instantaneous short circuits. The various cases, such as line to line short circuits, line to neutral short circuits, etc., have been considered in great detail. Much work has been published on the calculation of forces on bus structures and switches. However, it is believed that very little, if any, work has been published concerning the forces exerted on the windings of rotating machines during transient conditions.

A very brief consideration of the magnitudes of the short circuit currents and the proximity of these in the coil sides will quickly convince one of the importance of these forces. Peak values of 50,000 amperes in parallel conductors with a spacing of about 1¾ in. from center line to center line of the coil sides is quite a reasonable possibility in well designed machines of only moderately large ratings.

Three things are necessary in the study:

1. The determination of short-circuit currents,
2. The determination of the flux fields, and
3. Methods of calculating the forces exerted on the conductors after the currents and the flux fields are known.

The peak value of the armature current per coil side can be determined from the works of various authors.[1,2] In this paper, it will be assumed that the armature currents can be computed with reasonable accuracy, (see Appendix A). The other currents, or perhaps it should be said magnetomotive forces, will be determined through the very useful principle applied by the same authors, namely, that of the tendency for currents to flow in such directions as to maintain constant flux interlinkages in all the closed electric circuits in the metallic parts of the machine.

The flux distributions will be established by means of the relation $\int H' d\,l' = 0.4\,\pi\,I$ (see Appendix B). The usefulness and applicability of this principle has been thoroughly demonstrated by the quite accurate solutions of a number of the more important two dimensional flux fields in electrical machines.[3,8,12]

The forces will be calculated in this paper for two dimensional fields by one of three methods; each of these will be demonstrated later in detail. The first, is based on the use of images, and that the force exerted between two parallel conductors is proportional to the product of the currents, to the length of the conductors, and inversely proportional to the distance between the conductors.[4,5]

The second method is one which is very commonly employed. It is based on the rate of change in interlinkage (and, hence, of stored energy) with the displacement of a conductor while the currents are maintained constant. The third method is based on the fact that the force on any current carrying conductor existing in an electric field can be determined from $\int H^2\,d\,s$, taken over some surface surrounding the conductor.[6]

In one instance the force will be computed by each of these three methods to show that for the same boundary conditions, all give the same results. In other cases, it may then be assumed that the most convenient method is the best. However, the third method mentioned above will appear to be the most promising where saturation must be considered. This is very

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1. For references see Bibliography.

commonly the case, because the enormous currents necessary to produce forces of real consequence are often so situated that they do saturate some of the adjacent iron parts.

B. Division of Problem. The problem is arranged in parts according to the most convenient divisions of the flux fields. These will be taken up as follows:

1. Forces on conductors in slots.
2. Forces within either layer of the conical surface of the end winding exerted on the sides of the coils.
3. Forces on the straight coil extension from the slot.
4. Forces on the phase connecting rings.
5. Forces on the whole conical surface of the end winding.

II. Detailed Discussion of Forces during Short Circuit

A. Forces on Conductors in Slots

In the study of the forces acting on the embedded portions of the armature conductors, there are three main problems to be considered, *i. e.*:

1. Is the magnitude of the compressive force on the coil sides great enough to damage or rupture the insulation?

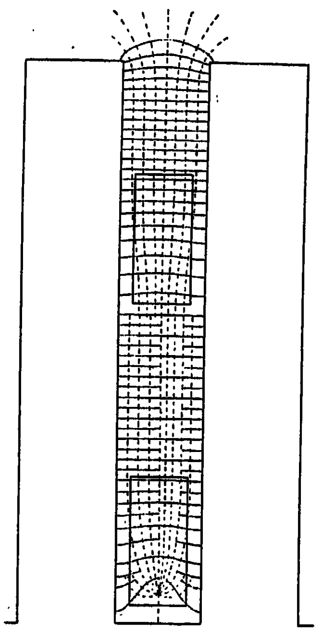


FIG. 1—CURRENTS EQUAL AND IN THE SAME DIRECTION

Iron of infinite permeability and resistivity

2. Are there repulsive forces between coil sides which might send a coil into the air gap (carrying the stator wedge with it)?
3. Are there forces which may rend apart the strands of one coil side?

As previously mentioned, it is desirable in some one instance to use all three of the methods for calculating the forces, *i. e.*, those involving—(1) images, (2) change of interlinkage with displacement, and (3) integral of H^2 around each conductor. This will be done for the case of embedded armature conductors when saturation is not considered.

Figs. 1, 2, and 3 illustrate the flux distributions in rectangular slots for three different current values. (These are taken from an article on graphical field mapping,[3,11] where they were drawn in accordance with the principle outlined in Appendix B of this paper). Substantially the same results were obtained in a later

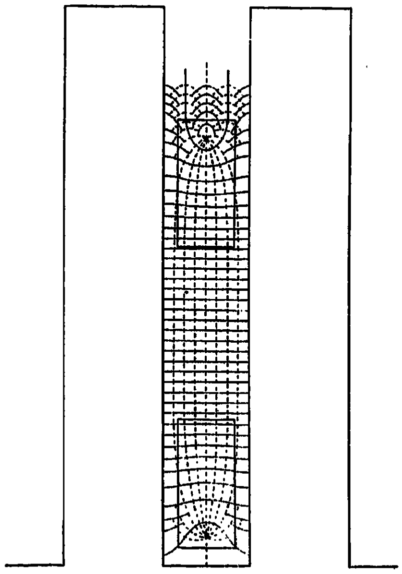


FIG. 2—CURRENTS EQUAL IN VALUE BUT OPPOSITE IN DIRECTION

Iron of infinite permeability and resistivity

paper by Messrs. Robertson and Terry, who made a very careful mathematical analysis.[7]

Fig. 1 represents the current conditions on a single-phase line-to-neutral short circuit in machines with an armature throw greater than ⅔, or a single-phase line-to-line short circuit with any commercially practicable coil throw. Fig. 2 represents some instantaneous condition during short circuit on a machine with a chorded winding, while Fig. 3 corresponds to some other instantaneous relation. These figures illustrate possible flux and current relations for a number of short-circuit conditions if saturation can be neglected. The effect of saturation will be considered later.

Calculation by the Use of Images. By comparing Figs. 1 and 4, it will be seen that the influence of the iron boundaries of the former are replaced by an infinite series of conductors in the latter.[8] (In Appendix C are listed the more usual boundary conditions found in electrical apparatus which can be represented or replaced by appropriate series of images.) It will be found that the corresponding conductors, shown in Figs. 1 and 4, not only carry exactly the same currents, but exist in flux fields of identically the same form and densities. It follows that the forces exerted on the conductors must be the same in the two cases. With

some modifications, the forces will be calculated from the conditions shown in Fig. 4.

Methods are available for considering the shape, dimensions, and separation of rectangular conductors

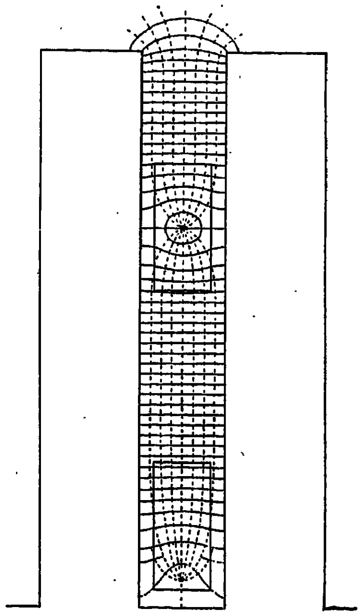


FIG. 3—CURRENT IN THE UPPER CONDUCTOR TWICE THAT OF THE LOWER AND IN THE OPPOSITE DIRECTION

Iron of infinite permeability and resistivity

in computing forces, if adjacent sides of the conductors are parallel.[4,5] However, there do not seem to be any methods worked out for the case of conductors placed in other positions relative to one another. It will be assumed for the present that the current in each conductor in Fig. 4 is concentrated at the center.

Then the force between two parallel line conductors in Fig. 4 will be

$$F = \frac{2}{445 \times (10)^5} \times \frac{I_2 I_n}{a} \qquad (1)^4$$

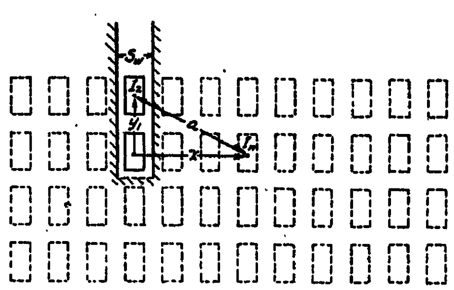


FIG. 4—REPLACEMENT OF THE SLOT SIDES OF FIG. 1 BY AN INFINITE SERIES OF CONDUCTORS, TO OBTAIN THE IDENTICAL FLUX FIELD

where F = force in lb. per linear in. of conductor.
I_2 = current in one conductor.
I_n = current in the other conductor.
a = distance between the conductors in inches.

Then in Fig. 4, the total force on the upper conductor is

$$F = \sum_{n=-\infty}^{n=+\infty} \frac{2}{445\,(10)^5} \, \frac{I_2 I_n}{a} \qquad (2)$$

also $$a = \sqrt{y^2 + x^2}$$

From symmetry, it can be seen that the forces in the x direction cancel, because corresponding to every pull to the right there is a duplicate one to the left.

Then the y component of force is

$$F_y = \sum_{n=-\infty}^{n=+\infty} \frac{2}{445\,(10)^5} \, \frac{I_2 I_n}{\sqrt{y^2 + x_n^2}} \, \frac{y}{\sqrt{y^2 + x_n^2}} \qquad (3)$$

$$F_y = \sum_{n=-\infty}^{n=+\infty} \frac{2}{445\,(10)^5} \, \frac{I_2 I_n y}{y^2 + x_n^2} \qquad (4)$$

To avoid the labor of making this summation to values where the contributions to F_y are negligible, a further simplification may be made. It will be observed that $I_n = I_2$. If each value of I_n is assumed to be spread out evenly so that the group form a sheet

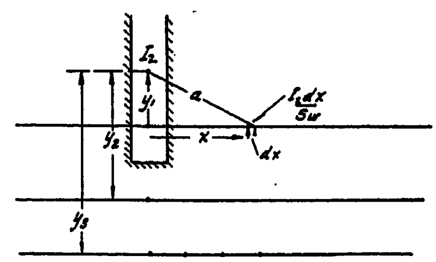


FIG. 5—REPLACEMENT OF CERTAIN SERIES OF CONDUCTORS IN FIG. 4 TO AID IN CALCULATING THE APPROXIMATE FORCES

through the centers of the conductors, instead of being assumed concentrated at the centers, then

$$I_n = I_2 \frac{d\,x}{S_w} \qquad (5)$$

and the total force in the y direction, from Fig. 5, is

$$F_y = \sum_{y=y_1}^{y=y_3} \int_{x=-\infty}^{x=+\infty} \frac{2\,I_2^2}{445\,(10)^5\,S_w} \, \frac{y\,(d\,x)}{(y^2 + x^2)} \qquad (6)$$

$$F_y = \frac{2\,I_2^2}{445\,(10)^5\,S_w} \sum_{y=y_1}^{y=y_3} \tan^{-1}\left(\frac{x}{y}\right)\Bigg]_{x=-\infty}^{x=+\infty} \qquad (7)$$

$$F_y = 14.1 \times 10^{-8} \frac{I_2^2}{S_w} \text{ multiplied} \qquad (8)$$

by [Number of layers below the conductor minus the number of layers above the conductor]

Where the layers are both imaged and real, as shown in Fig. 5.

In Fig. 1, where the currents are equal and in the same direction,

For the upper conductor,

$$ {}_2F_y = 42.3 \times 10^{-8} \times \frac{I_2^2}{S_w} \tag{9} $$

For the lower conductor,

$$ {}_1F_y = 14.1 \times 10^{-8} \times \frac{I_2^2}{S_w} \tag{10} $$

These forces are toward the base of the slot.

Calculation of the Force from the Rate of Change of Interlinkage. This method is very commonly employed. In the following case, it is based on Maxwell's equations for the stored magnetic energy in ergs in two electric circuits, *i. e.*

$$ 100\, W' = \left(\frac{I_1^2\, L_1'}{2} + \frac{I_2^2\, L_2'}{2} + I_1\, I_2\, M' \right) \tag{11} $$

The single-phase short circuit will be considered. Then

$$ I_1 = I_2 \tag{12} $$

If, for the instant when the current is at the peak value, a conductor is allowed to move by a small amount, then

$$ d\, W_y' = F_y'\, (d\, y') \tag{13} $$

or

$$ d\, W_x' = F_x'\, (d\, x') \tag{14} $$

But the work done must be at the expense of the stored energy, and the forces in lb. per in. of conductor are

$$ F_y = 8.85\, \frac{I_2^2}{2} \left(\frac{d\, L_1}{d\, y} + \frac{d\, L_2}{d\, y} + 2 \frac{d\, M}{d\, y} \right) \tag{15} $$

$$ F_x = 8.85\, \frac{I_2^2}{2} \left(\frac{d\, L_1}{d\, x} + \frac{d\, L_2}{d\, x} + 2 \frac{d\, M}{d\, x} \right) \tag{16} $$

As before, the x components of the force will be considered first. The values of L_1, L_2 and M are single valued and continuous functions of the displacement. In Figs. 1, 2, and 3, the values of L_1, L_2 and M may either increase, decrease or remain constant, but it will be the same for a motion $+ \Delta x$ as for $- \Delta x$. Then

$$ \frac{d\, L_1}{d\, x} = 0, \frac{d\, L_2}{d\, x} = 0, \text{ and } \frac{d\, M}{d\, x} = 0, \text{ individually,} $$

so that

$$ F_x = 0 \tag{17} $$

(as was found before from the solution by the aid of images).

The forces in the y direction will now be considered. Robertson and Terry[7] made calculations which showed the usual assumption was a good one, namely, that the flux went straight across the slot. Proceeding on this basis, suppose that the upper conductor is moved downward a distance $d\, y$.

Then

$$ \frac{d\, L_1}{d\, y} = \frac{d}{d\, y} \left[\frac{N_1\, \phi_1}{I_1} (10^{-8}) \right] = 0 \tag{18} $$

$$ \frac{d\, L_2}{d\, y} = \frac{d}{d\, y} \left[\frac{N_2\, \phi_2}{I_2} (10^{-8}) \right] \tag{19} $$

$$ \frac{d\, L_2}{d\, y} = \frac{3.19}{S_w} (10^{-8}) \tag{20} $$

$$ \frac{d\, M}{d\, y} = \frac{d}{d\, y} \left[\frac{N_1\, \phi_m}{I_2} (10^{-8}) \right] = \frac{319\, (10^{-8})}{S_w} \tag{21} $$

Substituting equations (18), (20), and (21) in (15)

$$ {}_2F_y = 8.85\, [(3.19 + 2 \times 3.19) \times 10^{-8}]\, \frac{I_2^2}{2} \tag{23} $$

$$ {}_2F_y = 42.45 \times 10^{-8}\, \frac{I_2^2}{S_w} \tag{24} $$

By supposing that the lower conductor is moved downward, and the upper held fast, it will be found that

$$ {}_1F_y = 14.15 \times 10^{-8}\, \frac{I_2^2}{S_w} \tag{25} $$

Equations (24) and (25) are in very close agreement with equations (9) and (10), respectively.

Calculation of the Forces from the Integral of H^2 Around the Conductor. Any surface will be chosen which surrounds a conductor. It will be imagined that the chosen boundary is rigid, and that forces exist between this surface and the conductor. The forces on the surface will act as follows: there will be tension along the flux tubes producing a force in dynes per unit of area.

$$ F' = \frac{(H')^2}{8\, \pi} \tag{26} $$

and there will be pressure per unit of area exerted perpendicular to the flux surfaces (designated by a negative sign).

$$ F' = - \frac{(H')^2}{8\, \pi} \tag{27} $$

(H' = lines per sq. cm.)

The force on the conductor will be equal and opposite to that acting on the surface. (What is believed to be a new proof of this principle is given in Appendix D. It is a proof which depends only on the more commonly used laws of electricity and magnetism, and which requires no detailed mathematical study).

Converted into units of lb. per sq. in. and lines per sq. in., equations (26) and (27) become

$$ F = +\, 0.0139 \left(\frac{H}{1000} \right)^2 \tag{28} $$

and

$$ F = -\, 0.0139 \left(\frac{H}{1000} \right)^2 \tag{29} $$

respectively.

Applying equation (29) to the conditions indicated by Fig. (1), it is found that between conductors $H_1 = 3.19 \dfrac{I_2}{S_w}$ and above the upper conductor

$H_2 = 2 \times 3.19 \dfrac{I_2}{S_w}$, and the same results are found for

${}_2F_y$ and ${}_1F_y$ as are given by equations (24) and (25), respectively. Since the pulls on the two sides of the slot are equal and opposite, $F_x = 0$ (as was found before).

Forces Tending to Drive a Conductor out of the Slot. In any case where the winding pitch is between ⅔ and full pitch, a three-phase short circuit may be expected to produce a flux distribution at one instant somewhat like that shown in Fig. 2, where the currents are equal but opposite in direction.

It can be shown by any of the three methods developed that for Fig. 2 (when saturation is neglected)

$$ {}_2F_y = -\,14.15 \times 10^{-8} \frac{I_2^{\,2}}{S_w} \tag{30} $$

The minus sign indicates a force tending to drive the upper conductor out of the slot. Also

$$ {}_1F_y = +\,14.15 \times 10^{-8} \frac{I_2^{\,2}}{S_w} \tag{31} $$

and acts toward the bottom of the slot.

It will be found that the force ${}_2F_y$ will be considerably less than the maximum value existing on a single-phase short circuit. However, it is still important, because the wedge must carry the load. This force should be given consideration, particularly in machines

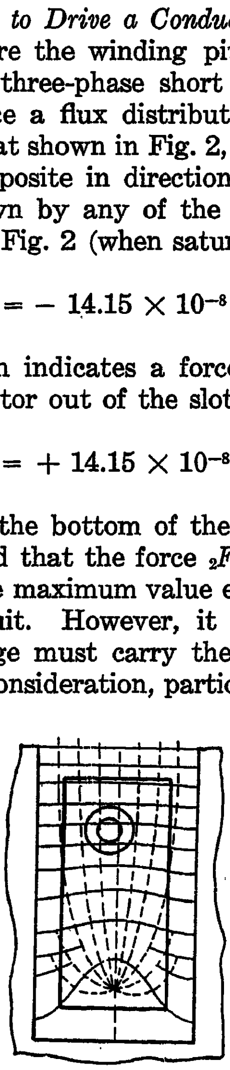


Fig. 6—Section of Fig. 1 with a Small Part of the Conductor Electrically in Parallel but Insulated from the Remainder

which can have high currents per slot, and which have wide slots.

If the coil were slightly loose so that the wedge could receive a series of impact blows (which would arrive at twice the normal electrical frequency of the machine), the possibility of failure would be considerably greater.

Forces on Individual Strands. It is intended, next, to determine whether there are any electromagnetic forces tending to separate the strands of any armature conductor. It will be assumed, first, that a small cylindrical hole is cut through a coil, as shown in Fig. 6. In this hole there is one small conductor, which is electrically in parallel with the main conductor, but the two are not in electrical contact at the section shown. The flux density at this point will be just the same as if the insulating space surrounding this strand were of conducting material,

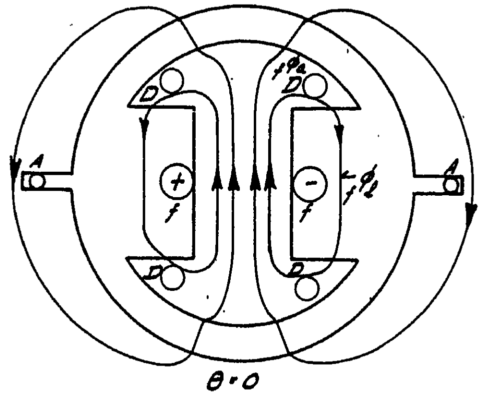


Fig. 7—Diagrammatic Sketch for the Instant before Short Circuit

for this space may be assumed to be very small. By making the hole extremely small, the direction of the force is more easily perceived. The flux density H' (due to the main conductor) must be single valued, so that as the isolated conductor is made smaller the main field on its two sides becomes more and more nearly parallel. The force acting on this conductor is

$$ \Delta F' = H' \frac{(\Delta I)}{10} \tag{32} $$

and is in the direction of the weaker resultant field. This is along the ampere turn line toward the m. m. f. center. Hence, all parts of the conductor are compressed toward the m. m. f. center. The strands further out are in stronger fields. They are acted on with greater force so that there are no effects due to the inertia of the strands which may tend to separate them. From an examination of Figs. 1, 2, and 3, it will be seen that there probably are no combinations of current values possible in armature conductors, which will result in electromagnetic forces, tending to disrupt the coil sides by the separation of the strands. Any forces which separate the strands must be brought about by pulsating forces which press the whole conductor against its supports (bottom of the slot and the wedge) with such violence that the strands are shaken apart.

Reduction of Forces Due to Saturation. Saturation of the armature teeth will greatly reduce the forces. In order to consider this feature, a brief survey of the general flux distribution is necessary.

The particular condition which will be considered is that existing at the instant one-half cycle after a single-

phase line-to-neutral short circuit has occurred. Figs. 7 and 8 show the resultant flux immediately before the short circuit, and one-half cycle later, respectively.

It is assumed in Fig. 7 that the armature, A, is open-circuited, but that the field winding, f, is excited so as to maintain normal voltage at the generator terminals. No currents of fundamental frequency are flowing in the damping circuits D. The armature is short-circuited at the instant ($\theta = 0$) when the flux "trapped" in the electric circuits, A, D and f are as shown.

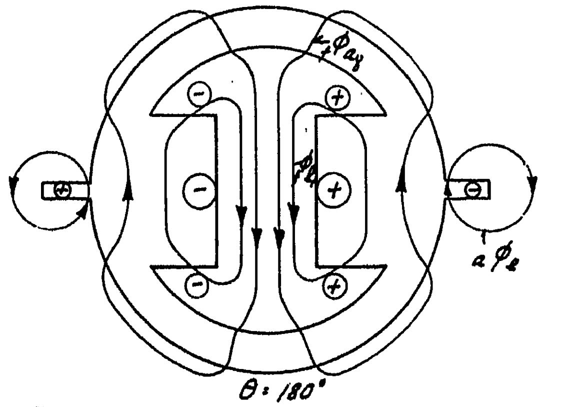


FIG. 8—DIAGRAMMATIC SKETCH FOR THE INSTANT ONE-HALF CYCLE AFTER THE SHORT CIRCUIT OCCURRED

It is assumed that in each circuit current will flow which tends to maintain constant flux linkages in its own particular circuit.

Then when the rotor has turned 180 electrical deg., the resultant flux will be as shown diagrammatically in Fig. 8. The sum of the gap and field leakage flux paths, and constant interlinkages were assumed, the m. m. f. of each member would be practically equal. Oscillographic records show that the currents of the field winding, f, will not produce an m. m. f. anywhere nearly comparable with that of the armature winding during the first cycle after the short circuit occurs. As the mutual reactance of the rotor and stator circuits is high, there must be a very large current flowing on the surface of the rotor. The leakage path for this current has a greater reluctance than that of the armature. From Fig. 7 the initial flux linkages of the rotor are greater than those of the stator. Therefore, in order to maintain these very nearly the same in Fig. 8 as in Fig. 7, the total rotor m. m. f. must be greater than that of the stator. This means that at a very great distance from all circuits the total m. m. f. of the rotor will prevail. Hence, there is a very slight amount of air gap flux threading both the armature and rotor circuits in a direction opposite to that of the armature leakage flux.

The total armature leakage flux probably will be somewhat greater than the no load air gap flux, because of the difference in distribution of the two fields. A less percentage of the leakage flux links all the winding. In addition to this, there must be enough armature flux to offset the linkage of the small amount of air gap flux which links both windings. The armature leakage flux will require relatively few ampere turns for the core compared with the number required for the teeth and slot.

The retaining ring leakage flux will be prevented from increasing greatly during the first half cycle by eddy

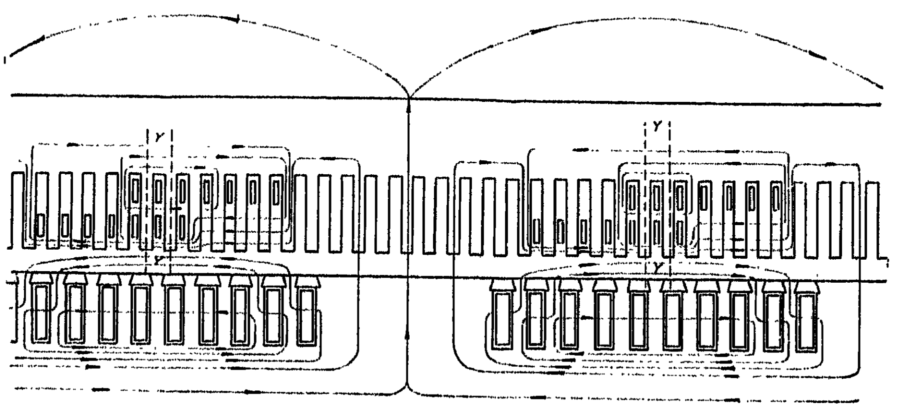


FIG. 9—APPROXIMATE DIRECTIONS OF THE FLUX IN THE GAP TEETH AND CORE

$({}_f\phi_g + {}_f\phi_l)$ must remain practically up to its initial value, because this constitutes the flux linkages of the rotor winding. However, nearly all of the gap flux must pass inside the armature conductors, because the latter must have a net interlinkage opposite to that which the gap flux, alone, would produce if it returned through the stator core. The armature must have sufficient leakage flux to maintain its interlinkages up to the initial value, and in the initial direction. If the stator and rotor had precisely equal leakage currents and also by saturation. Eddy currents in the sides of the rotor teeth will oppose increase in rotor slot leakage flux. Consequently, the air gap flux can decrease only slightly during the first half cycle. This means that the total rotor magnetomotive force due to the winding currents and rotor surface currents will exceed the total m. m. f. of the stator by an amount approximately equal to the no load normal voltage m. m. f.

If it were intended to map the complete flux field, cer-

tain steps would be necessary. Determine the magnitude of the armature current as described in Appendix A, or by any suitable method. Give to the rotor a m. m. f. greater than that of the stator by an amount approximately equal to the no load gap ampere turns. Determine the rotor winding ampere turns relative to the stator from tests on the nearest similar machine. Locate the remaining rotor current on the rotor surface opposite the stator windings. Draw the flux field for the non-magnetic parts by assuming no saturation. Complete the field in the iron on the assumption of slight saturation and uniform permeability. Calculate the ampere turns for the iron parts and attempt to redistribute the ampere turn lines to take care of this.

It is only intended here to consider the effects of saturation in a single slot pitch.

Fig. 9 shows the approximate direction of the flux field in the gap teeth and core on a single-phase line-to-neutral short circuit for the instant shown in Fig. 8.

The effect of saturation will be considered in the zones Y-Y of Fig. 9. The flux in this zone will travel nearly tangentially across the slot and teeth. Except for a negligible number of ampere turns required for the core, the ampere turn lines from the stator conduc-

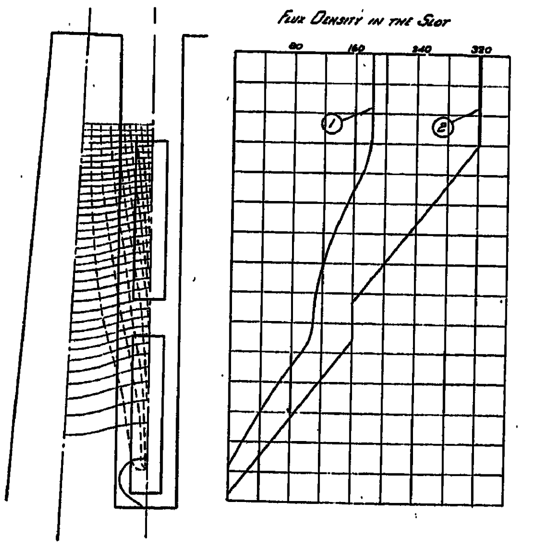


FIG. 10—DENSITIES IN THE SLOT AT Y-Y OF FIG. 9 CURVES SHOW SLOT DENSITIES FOR 50,000 AMPERES PER CONDUCTOR

(1) when saturation is considered, (2) when saturation is neglected and it is assumed that the flux goes straight across the slot

tors in this slot will proceed almost directly toward the rotor currents. These will spread enough to supply the requirements of half of each adjacent tooth as well as the slot itself. The values which will be used are approximately those which existed in an actual machine. There will be 50,000 amperes per coil side, or 100,000 ampere turns for the slot. The densities in the core are such as to require less than 1000 ampere turns in the iron back of the slot pitch, and hence can be neglected. Fig. 10 shows the densities in the slot with each conductor carrying 50,000 amperes, when the saturation of the teeth is neglected, and when it is considered.

By equations (28) and (29) the forces are as follows:

Force in lb. per in. of length

	Saturation neglected	Saturation considered
Electromagnetic force on upper conductor (toward base of slot)......	1062	695
Electromagnetic force on lower conductor (toward base of slot)......	354	210
Sum = total force on lower conductor (toward base of slot).........	1416	905

This shows that saturation is a most important factor to be considered in calculating the loading on the coil

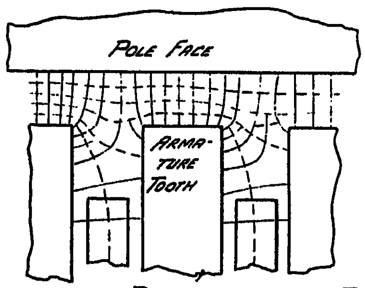


FIG. 11—DIFFERENCE IN DENSITIES ON THE TWO SIDES OF A TOOTH UNDER LOAD CONDITIONS

insulation in the slot. In Fig. 9 it is seen that for certain other conductors the flux will travel nearly radially in one tooth which bounds the slot, and it would be expected that saturation would have an even greater effect in reducing the force on these conductors. Due to the dissymmetry of the flux distributions in the adjacent teeth, there should be some tangential force exerted on the conductors.

Normal Torque of a Machine. While the torque of a rotating machine is not within the province of this paper, some mention probably should be made of it. It has been pointed out several times in the preceding paragraphs that when there is no appreciable saturation, there is no tangential force exerted on the conductors in the slot. In general, this approximates the normal running conditions of many machines. The torque must be found near the teeth tip in the difference in densities on the two sides (see Fig. 11). With saturation, the flux will not enter circumferential surfaces in a radial direction and some tangential pull will result from the corresponding components, at these surfaces. In the old surface wound machines the torque was carried almost entirely by the armature conductors.* It should be noted that when the field map has been drawn, equations (28) and (29) can be used to determine the forces exerted on the iron and copper

*This is not a new idea, but has been studied in part both theoretically and experimentally. See bibliography reference 13.
Prof. A. D. Moore has also used for some time in his lectures these general facts concerning torques.

parts in any portion of the field. This applies not only to rotating machines, but to contactors, and to any other apparatus in which the flux distribution can be determined.

Conclusions concerning the forces on conductors in armature slots.

1. The force pulsating at twice normal frequency and pressing the coils toward the bottom of the slot on a single-phase short circuit may have a value of 695 lb. per in. of conductor (or greater).

2. On three-phase short circuits in machines of less than full pitch, there will be forces tending to drive a conductor out into the air gap, carrying the wedge with it. These forces, while less than those just mentioned above, can be very serious if a coil is loose so that the forces on the wedge arrive as impact blows.

3. The forces exerted toward the sides of the slot are very much less, and only exist when the saturation in two adjacent teeth is appreciably different.

4. There are no electromagnetic forces directly acting to disrupt the conductors by separating the strands one from another. However, the hammering of the conductor on the bottom of the slot, if the conductor is loose, may cause some internal motion. This might be capable of wearing out the insulation between the strands very quickly.

B. Forces Within the Conical Surface of the End Winding

Fig. 12 indicates the approximate paths of the flux linking the armature end winding on a single-phase line-to-neutral short circuit. All currents in the parallel conductors are in the same direction, so that

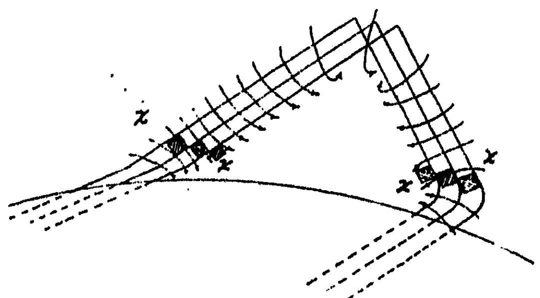


Fig. 12—Approximate Paths of the Flux Linking the Diamond Coil Armature End Winding

these coil sides tend to pull together. The maximum force will be exerted on the inside conductor at sections X-X, because the greatest concentration of flux is in this elbow of the phase group. Toward the outer or diamond ends of the coils there will be a force between the coil sides in the two layers tending to open out this angle. That is the coil ends have a tendency to bow out to a sort of semi-circular shape. The flux distribution around the semi-straight portion of the coil, between the inner elbow (X-X) and the diamond (outer) end, has much the same shape as if it were due to a group of long straight conductors in air, far removed from other metallic parts. By making just that assumption, the force on any conductor may be computed by the successive use of equation (1). Thus,

$$F = \frac{2}{445 \times 10^5} \; \frac{I^2}{a} \left(1 + \tfrac{1}{2} + \tfrac{1}{3} + \ldots + \frac{1}{N-1}\right) \quad (33)$$

Where:

I = maximum armature current per coil side.

a = spacing center to center between coil sides in one layer of the conical surface of the end winding.

N = number of coils per phase group.

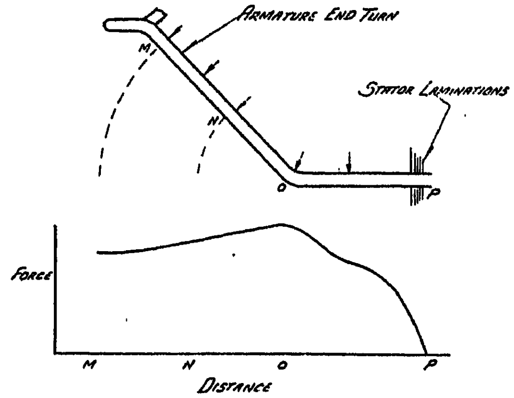


Fig. 13—Approximate Force against the Side of the Coil

As before, the correction factors for the shape of the conductors are neglected. These factors will reduce the force to some extent. There will be a different correction factor for the force between each pair of conductors, depending upon whether their spacings are a, $2\,a$, $3\,a$, or $(N - 1)\,a$, etc.

In order to calculate the force per inch of conductor within one layer of the conical end winding of the machine for which the last numerical example was computed, it is noted that

$$I = 50{,}000$$
$$a = 1.79$$
$$N = 7$$

Then from equation (33)

$$F = 154 \text{ lb. per in. of conductor.}$$

Fig. 13 shows the probable sort of force distribution in the plane of the windings based on the conditions indicated in Fig. 12.

Fig. 12 shows that greater densities exist at the inner bend of the coil. The force must fall off toward the outer end of the coil for there are less and less coil sides outside of the inner one. Then as the outer bend of the coil is reached the repulsion from the coil sides in the other layer of the phase group will tend to increase the force.

Conclusions concerning the forces on the conductors within the conical surface of the end winding.

1. The forces on a single-phase short circuit tend to pull all the conductors together within one layer of the conical end winding.

2. The force is greatest on the inner coil sides of the group at the bend (or elbow) of the coil nearest the frame. It decreases from there toward the outer bend of the diamond coil.

3. In between these two bends in the coil the force may be 150 lb. per in. of conductor, or greater, on the assumption that the force may be computed as would be done for long straight conductors in air. The fact that the space within the phase group is limited indicates that the force should be greater than calculated, but if the correction for the coil shape is neglected, this is compensated for to a certain degree.

4. This force is sufficient to distort the winding unless bracing blocks (or the equivalent) are located between coils at quite frequent intervals.

5. Conductors which are two strands wide are very much weaker than those which are one strand wide in the direction of this force. It is necessary that a manufacturer know the strength limitations of the coils and stay well within them. It should be noticed that while the resistance to shear between strands is very low, that the copper is held on the ends, so that tests on a short bar are not satisfactory. Undoubtedly testing coils to destruction on actual machines furnish the most reliable data on which to check calculations.

C. Forces on the Coil Extensions from the Frame

Tests on actual machines have shown that the straight parts of the coils extending from the slots over the retaining rings are almost as liable to failure as are the coil sides within either of the two layers of the conical end winding.

The conditions illustrated in conjunction with Figs. 7 and 8 will be used for the basis of the following calculations. It was concluded that at the instant indicated

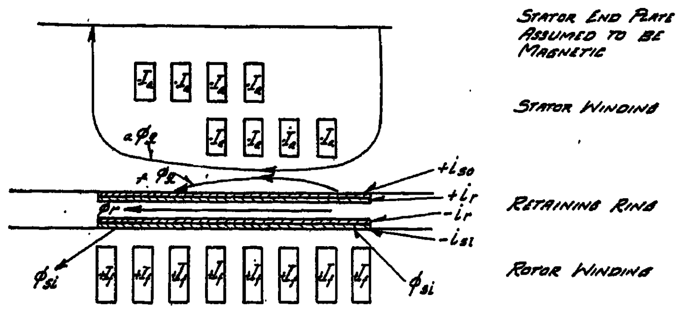


Fig. 14—Diagrammatic Sketch of the Currents Flowing in the End Zones Just Outside the Frame

by Fig. 8, the rotor m. m. f. was equal to that of the stator plus an amount approximately equal to the field m. m. f. at the no load normal voltage condition. This applied to the main magnetic circuit. A detailed study will be undertaken now in an attempt to picture the current and flux distributions just outside the ends of the "active" armature iron.

Figs. 14 and 15 indicate, in a diagrammatic way, the currents which must flow in this zone.

The currents indicated are as follows:

I_a = the armature current per coil side (as defined in Appendix A).

I_f = the current in the field winding for the instant shown in Fig. 8.

i_{so} = the rotor surface current on the outside of the rotor. This is practically the continuation of the damping currents of the rotor body out into the retaining ring. The straight

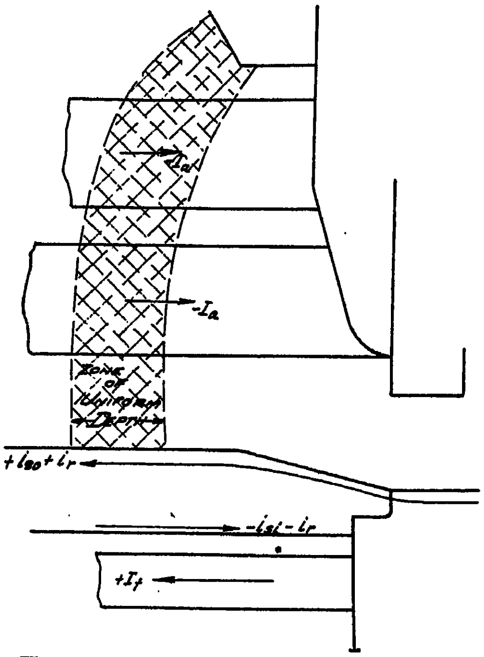


Fig. 15—View of Fig. 14 in the Radial Plane at the Centerline between Poles

parts of armature coils extending directly out from the slots furnish the m. m. f. to carry these currents out into the retaining ring to oppose the armature. If it were not for the arrangement of these armature conductors, there are reasons to believe that with a tapered magnetic retaining ring this surface current would turn and travel tangentially very soon after it left the rotor body. However, this seems impossible when the armature winding is so near, and this belief has been very forcefully upheld in a test to destruction. It is assumed, then, that this rotor surface current i_{so} travels axially across the outside surface of the tapered section of the retaining ring.

i_r = the transient current flowing in the retaining ring to oppose any change in the retaining ring leakage flux.

ϕ_r = the retaining ring leakage flux.

i_{si} = the retaining ring surface current on the inside surface which opposes any change in the flux entering or leaving the ring from the inside.

With the currents defined, it will now be possible to

consider the ampere turn surfaces. These emanate from the rotor field winding and pass through the retaining ring. Most of them terminate on the armature conductors which carry current in the opposite direction to the field windings. A few of these ampere turn surfaces go through the air gap and through part of the stator iron to terminate in the field windings on the other side of the pole.

The effects of the rotor surface currents must be considered. The current on the inner surface of the retaining rings, i_{si}, will be neglected. This is probably the wrong thing to do, but it is desired to be on the safe side in the force calculations. It is possible, and it even seems probable, that this current might nearly cancel the increase in m. m. f. in the end zone, due to the increase in field current, but this is neglected.

The net effect of the current i_r is practically zero. This component is shown by two current sheets. One is in the inner surface of the ring and one in the outer. These flow in opposite directions. What the inner sheet subtracts from the m. m. f. between a given pair of ampere turn surfaces, the outer adds in again.

ring. The real current sheet, i_{so}, will travel nearly axially outward under the straight part of the armature coil extensions, because it flows as a sort of image of the armature current.

Oscillographic records of armature and field winding currents show that the armature m. m. f. is much the greater of the two. Yet the constant interlinkage theory demands that the total rotor m. m. f. be slightly greater than the stator. This means that the m. m. f. of the rotor surface currents, i_{so}, is much greater than that of the rotor winding I_f at the instant shown in Figs. 8, 14, and 15. This real surface current, i_{so}, must be as much larger than the imaginary current sheet used to replace the saturation of the ring. The resultant current sheet of the real and imaginary one must have almost axial directions of flow under the armature coils. The strength of the stator m. m. f. may actually be the greater at a short distance out in the tapered section of the ring if the effect of the current sheet, i_{si}, on the inside of the ring is considered.

The purpose of the foregoing discussion of current and flux in the end zone near the tapered section of the re-

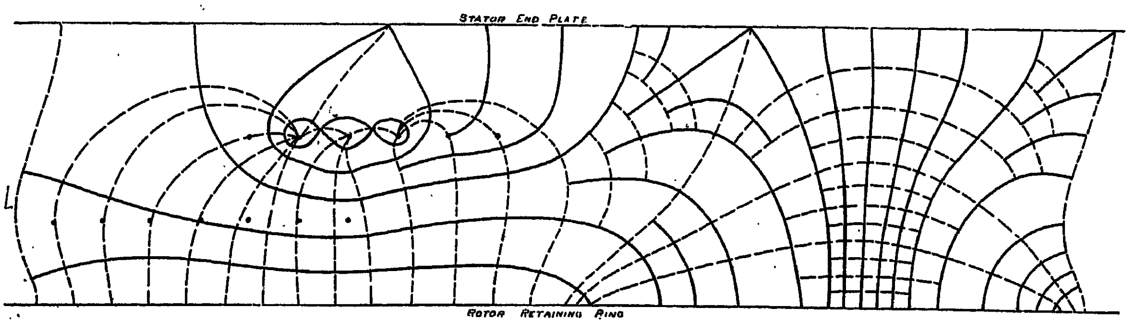


FIG. 16—FLUX FIELD, IN THE END ZONE JUST OUTSIDE THE END BELLS

Very small armature conductors are used for simplicity in mapping

There remains the rotor surface current, i_{so}, and a certain contribution from the rotor windings. The ampere turn surfaces arriving at the outer surface of the retaining ring can be replaced by an imaginary current sheet of just the right current density, which flows on a ring of infinite permeability. (The replacement of saturation by the suitable current sheet and unsaturated iron has been demonstrated by Th. Lehmann in some of his excellent papers concerning graphical field mapping.[9,10,11]) This imaginary current sheet may now be superposed on the real (transient) current sheet, i_{so}, flowing on the outside surface of the ring.

The directions of these two component current sheets are probably not the same.

The saturation in the ring is greatest in the tapered section. Consequently, the leakage flux in the ring will travel nearly axially across this section. A large proportion of the ampere turn surfaces maintaining this leakage flux will lie in the ring in fairly near circumferential directions. The imaginary current sheet used to replace this saturation must have the same directions as these ampere turn surfaces inside the

taining ring has been an attempt to get a graphic picture of the actual conditions. Some approximations will be made now to compute the forces on the armature windings.

A resultant or equivalent current sheet will be assumed to exist on the rotor retaining ring, and flowing axially outward from the rotor slots. It will have a uniform current density and a total m. m. f. equal to that of the armature plus the no load normal voltage rotor m. m. f. The flux to be considered will be assumed to remain within the zone of uniform width indicated in Fig. 15. (The direction of the flux is approximately perpendicular to the plane of that drawing.) Saturation in the stator end plate is neglected, because it is a magnetic parallel on the stator core. The magnitude of the eddy currents in this plate cannot be estimated satisfactorily. They will be neglected for the same reason that the rotor m. m. f. was assumed at its maximum possible value, *i. e.*, to be on the safe side. On this basis, Fig. 16 was drawn (using small armature conductors), and Fig. 17 drawn from Fig. 16. The forces on the conductors may be computed from the

integral of H^2 taken around each one. The way the flux encircles the group of coils indicates appreciable tangential forces on the outer ones of the group. However, the coils may be well braced against this by roped-in blocking. The highest radial forces occur on the coil sides in the center of the group. A very easy means of approximating this force becomes evident from the work done concerning the conductors embedded in slots. It is as though the conductors lay in slots of width equal to the slot pitch. See section Y'-Y', Fig. 17. From equation (24), it seems the force on the conductor nearest the retaining ring will be about

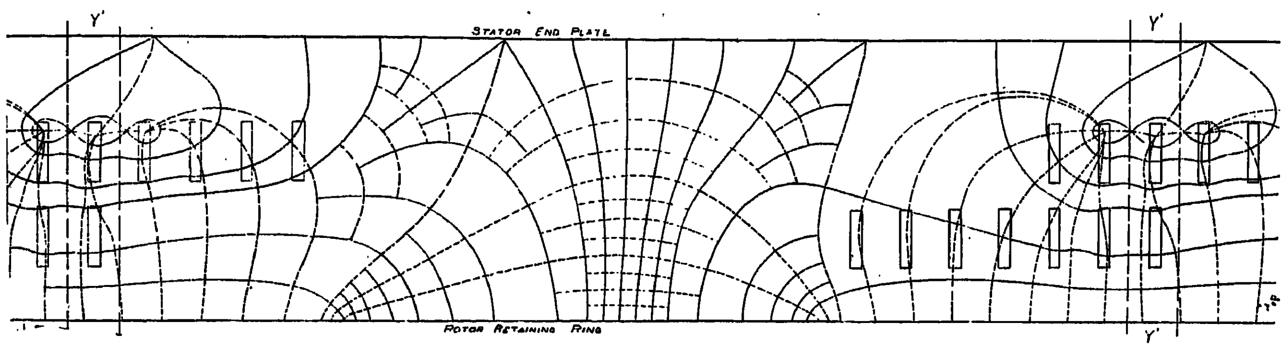


FIG. 17—FIG. 16 REDRAWN FOR ARMATURE CONDUCTORS OF NORMAL SIZE

$$_2F_y = 42.45\ (10^{-8})\ \frac{I_2^2}{q} \qquad (34)$$

where q = the slot pitch in inches.
If $q = 2.185$ and $I_2 = 50{,}000$, then $_2F_y = 485$ lb. per running in. of conductor.

Fig. 18 indicates the probable sort of variation load against the edge of the coil.

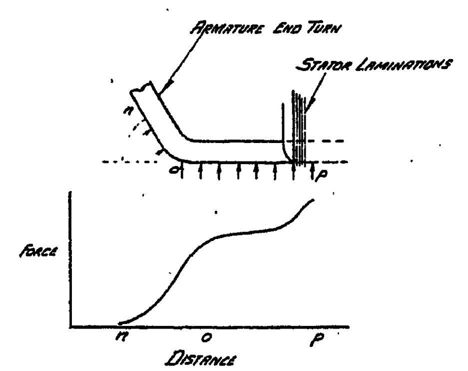


FIG. 18—APPROXIMATE FORCE AGAINST THE EDGE OF THE COIL

Conclusions concerning the forces on the coil extensions from the frame.

1. There are fairly large tangential forces on the outer conductors of the phase group, similar to those within each layer of the conical end winding. However, these forces operate against the edges of the strands composing the coil sides. Bracing blocks are always inserted, and these can be made to give adequate support against such forces.

2. The forces acting radially outward are of appreciable magnitude. These act against the coil in the direction in which the individual strands are the weakest, but there are many of them in the coil side. Tension and compression along these strands operate to prevent failure. The force falls off with distance from the slot toward the first bend or elbow of the coil, and very rapidly beyond the bend.

3. Experience indicates that this is a less likely place for failure to occur than within a layer of the conical surface of the end winding, but if the straight extension from the slots is long, special bracing should be supplied.

4. A matter deserving real consideration is the tendency to twist the conductor due to the radial and tangential force exerted on the bend nearest the frame of the coil side at the inside of the phase group. Careful bracing on each side of this bend (see section X-X, Fig. 12) must be used to so stiffen the mechanical resistance of the coil and supports that it will remove this possibility of failure.

D. FORCES ON THE PHASE CONNECTING RINGS

Rectangular copper straps are bent into semi-circular arcs, and used to connect the terminals of the machine to the ends of the various phase groups. These phase connecting rings are considerably closer to each other than to any heavy iron parts. They are located in a relatively weak part of the field of the armature end windings. The radius of curvature of the rings is rather large. Therefore, it seems a reasonable approximation to assume that the forces on the phase connecting rings will be about the same as if they were straight conductors in air well removed from other metallic parts.

The forces can be calculated by equation (1). However, the directions of the currents must be determined from the conditions of the short circuit. The usual forms of bracing, blocking, and clamping are well known. On the whole, they are easy to apply, but special attention must be given to the ends of the phase connecting rings where they join the coil ends, in the machines in which the loading is large, for this is an inherently weak place in one turn coils.

E. FORCES ON THE WHOLE PHASE GROUP IN THE CONICAL END WINDING

A quantitative solution has not been worked out

for estimating these forces. Probably their directions are almost as important. The currents on the retaining ring (the real transient current and the imaginary current used to replace the saturation of the ring) will tend to produce an approximately outward force on the phase group. The coils are rather centrally located between the iron parts of the frame and end-bell, so that the effect of these latter parts should tend to cancel out.

It would be very desirable to have a definite, but not too great force, pressing the coils outward toward coil supports which are mounted on the frame. Such an arrangement would eliminate any need for bolts through the winding to hold it back toward the frame. There are two ways to accomplish this. Laminated iron near the stator end plate to furnish a strong attraction would achieve this result, but it is commercially a rather impractical measure. A good conductor on the inner end-bell would carry eddy currents which would offer a force of repulsion to the armature winding and tend to force it back toward the frame. This is a practical expedient. An aluminum diffuser for a double entrance fan will serve this purpose. However, it is possible such a thing might be very badly done. If the entire inner end-bell were made of aluminum or copper, it would probably have high losses, and possibly excessive heating under normal load conditions. The reason would be that the path of the armature leakage flux would be too greatly restricted. This damper would have to render a magnetomotive force almost equal to that of the armature. The smaller damper will carry only a relatively small current and loss at normal load. The tremendous increase in flux on short circuit will give sufficient current to produce a definite force in the desired direction.

In addition to the forces just discussed where the resultant lies in a radial plane, there must be a tangential force acting on the phase group in the direction opposite to that of rotation. This torque will be due to the losses occurring in the end-bell, end plate, etc. It is as though these iron parts were the secondary, and the stator winding the primary of a surface wound induction motor, so that the burden of the torque falls on the armature conductors.

Some further considerations of the forces are given in Appendix E for certain limiting cases.

SUMMARY

Fairly detailed conclusions have been given at the end of each section in the paper, so only a brief summary will be made here.

Three methods of calculating the force exerted on current carrying conductors have been demonstrated. The method involving the use of images can only be used when there is no appreciable degree of saturation. (The most common configurations which can be imaged are summarized in the Appendix C). The method involving the change of flux interlinkages is most useful where a reasonably simple mathematical expression can be obtained; but if the method involves the difference of two large values of interlinkages by the use of graphical field maps, it is not satisfactory. The method which uses the $\int H^2\,d\,s$ over any surface enclosing a conductor is the most generally applicable. It frequently involves the plotting of one rather difficult field map, but in such a case there is probably no way of avoiding this labor. (A simple proof is given in Appendix D for the basic principle of this last method for the calculation of the forces.)

The forces exerted on the embedded armature conductors during short circuit are computed and the great influence of saturation is illustrated. It is shown that there are no electromagnetic forces tending to disrupt the coil sides by rending apart the strands. A graphical picture is given for the normal torque of a machine. The forces between coil sides in one layer of the conical end winding are computed. The forces on the straight coil extensions from the frame are approximated. The forces on the whole conical surface are discussed, and methods of causing the force to be definitely toward the frame are pointed out. The applicability of simple formula for approximating the forces on the phase connecting rings is also pointed out.

ACKNOWLEDGMENTS

The writer greatly appreciates the assistance of Messrs. M. G. Leonard, A. M. Harrison, M. R. Lory, and R. D. Reed, for their assistance in making the field maps, and also appreciates the helpful discussions with Messrs. L. A. Kilgore and C. M. Laffoon.*

Appendix A

ARMATURE SHORT-CIRCUIT CURRENT PER COIL SIDE

The maximum possible peak current per coil side which exists at the end of the first half cycle after an instantaneous line-to-neutral short circuit is often computed by the approximate formula

$$I = \frac{I_{rms} \times 1.5 \times 2\sqrt{2} \times .9}{X_d''} \tag{35}$$

$$I = 3.82\,\frac{I_{rms}}{X_d''} \tag{36}$$

where,

I = maximum short-circuit current per coil side.

I_{rms} = r. m. s. value of normal load current per coil side.

X_d'' = subtransient reactance expressed as a decimal fraction.

*All of the Westinghouse Company.

Appendix B

Basis of Graphical Field Mapping

The basis for graphically mapping two dimensional flux fields, which is used in this article, has been published several times,[3,8,12] but is given here in an abbreviated form for the sake of completeness.

Fig. 19 illustrates the flux field of a salient pole machine at the no-load normal voltage condition.

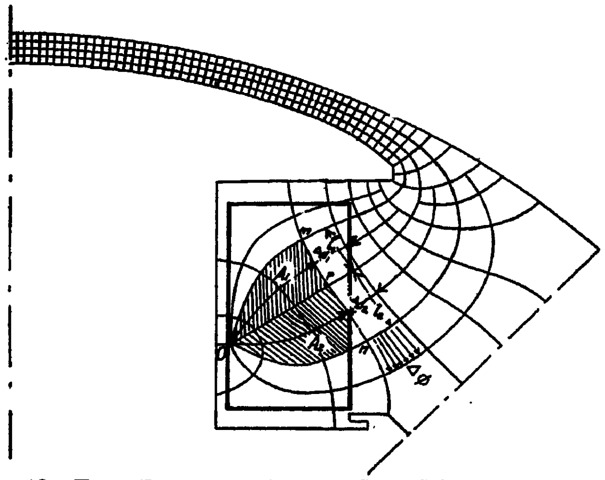


FIG. 19—FLUX FIELD OF A SALIENT-POLE MACHINE AT THE NO-LOAD NORMAL VOLTAGE CONDITION

It will be assumed correct, and the relations necessary that it be the true field will be illustrated (uniqueness is assumed). If a unit pole is moved around the path $o\,p\,n\,o$ linking the current I_2 and area A_2 the work done is $\int H'\,d\,l' = 0.4\,\pi\,I_2$. This is all done along the flux line $p-n$ of length l_1'. If the elemental tube of flux $\Delta\,\phi$ considered, has a mean width $(\Delta\,d_2')$ and mean density H_2' in this length l_2', then

$$H_2'\,l_2' = 0.4\,\pi\,I_2 \tag{37}$$

$$\frac{(\Delta\,\phi)\,l_2'}{\Delta\,d_2'} = 0.4\,\pi\,I_2 \tag{38}$$

Similarly for the path

$$\frac{(\Delta\,\phi)\,l_1'}{\Delta\,d_1'} = 0.4\,\pi\,I_1 \tag{39}$$

From the last two equations

$$\frac{l_1'/\Delta\,d_1'}{l_2'/\Delta\,d_2'} = \frac{R_1}{R_2} = \frac{I_1}{I_2} = \frac{A_1}{A_2} \tag{40}$$

where R is the reluctance and uniform current density is assumed so that I is proportional to A. The last series of relations is sufficient for graphically mapping any two dimensional field in the non-magnetic parts, if the currents are located and the saturation known approximately.

Appendix C

Images[6,8]

The most common two dimensional field in which the boundaries may be replaced by the use of other conductors are those of

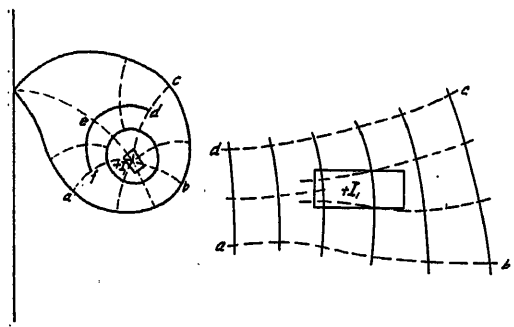
1. Conductors between two planes which meet at a certain angle. The angle expressed in degrees when multiplied by some integer must give 180 deg.
2. Conductors between parallel planes.
3. Conductors in rectangular slots.
4. Conductors in completely closed rectangles.

In the first three cases the plane sides should have either infinite permeability (and if an alternating field is considered infinite resistivity; or unit permeability and zero resistivity). In the fourth case if the boundary is of infinite permeability there must be as much current in one direction as the other so that no ampere turn lines penetrate the boundary. If the surrounding surface is of zero resistivity, it is not necessary that the sum of the currents in the enclosed conductors be zero for the surface will carry currents to receive any excess ampere turns from the conductors.

Appendix D

Calculation of Force from $\int H^2\,d\,s$

It is apparent that every element of current tends to establish a field of force around it in such a manner that the flux lines form closed loops. Consequently at certain conductors in any field the ampere turn lines, or lines of no work, must converge at points of no flux density. These points will be called m. m. f. centers. However, not all current carrying conductors may sustain a point of zero density. The centers which they might sustain if excited alone are submerged in



A B

FIG. 20—A. A CONDUCTOR WHICH MAINTAINS A M. M. F. CENTER

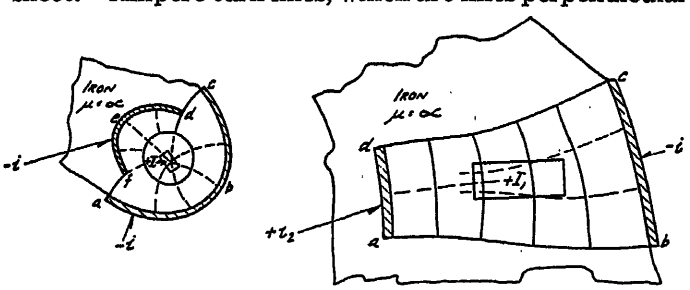
B. A CONDUCTOR WHICH DOES NOT MAINTAIN A M. M. F. CENTER

the main field and only swirls or waves may be left to indicate the tendency (See the upper conductor in Fig. 1). The forces exerted will be considered for these two cases, namely, (1) when the conductor contains an m. m. f. center and, (2), when it does not.

These two possibilities are illustrated in Figs. 20A and 20B, respectively. Figs. 21A and 21B show exactly the same conductors existing in exactly similar fields, but with different boundary conditions. These are

strictly two dimensional problems. Unit depth perpendicular to the drawing will be assumed. In Fig. 21A two current sheets, $a\ b\ c$ and $d\ e\ f$, have replaced the flux lines of Fig. 20A, which were in these positions. The current in these sheets travels parallel to that of the conductor, but in the opposite direction. The current densities are such that the ampere turn lines leaving the conductor may terminate in these sheets at precisely the points where they formerly crossed a flux line.

In Fig. 21A the lines $c\ d$ and $f\ a$ form boundaries for the iron of infinite permeability and infinite resistivity and are so arranged that the flux lines link the rectangular conductor in the same direction as before. In Fig. 20A, these were portions of ampere turn lines. In both cases the flux crosses these lines perpendicularly. Thus it is seen that the boundaries of flux tubes, which appear in these two dimensional fields, may be replaced by sheets of current which travel perpendicular to the plane of the drawing, and which have such current density and sign that the ampere turn lines arriving there may terminate in the current sheet. Ampere turn lines, which are lines perpendicular



A B

Fig. 21—A. Fig. 20A with Special Boundary Conditions to Isolate the Conductor

B.—Fig. 20B with Special Conditions to Isolate the Conductor

to flux may be replaced by surfaces of imaginary iron bodies that have infinite permeability (and for a-c. fields, infinite resistivity).

Fig. 20B represents a current carrying conductor without an m. m. f. center. It has been arranged in Fig. 21B with a current sheet of like sign at $a - d$, and one of opposite sign at $b - c$. The latter is numerically equal to the sum of the other two currents, but of opposite sign. The ampere turn lines $d - c$ and $a - b$ of Fig. 20B are iron surfaces in Fig. 21B. Again the magnetic circuit in the iron is so arranged that the flux lines link the original conductor in the same manner as before.

The problem is to determine the forces on the rectangular conductors. These are, obviously, the same in Fig. 21A as in Fig. 20A, and the same in Fig. 21B as in Fig. 20B. In Figs. 21A and 21B the forces on the rectangular conductor must be equal and opposite to the integral of the forces taken over the boundary materials in each case. It will be found easier to make the computations on the boundary.

The force on a small area of the material carrying the current sheet ($a\ b\ c$ Fig. 21A) will be considered first. This element of the conducting sheet will be chosen so small that it can be considered as plane surface. Two views of it are shown in Figs. 22A and 22B.

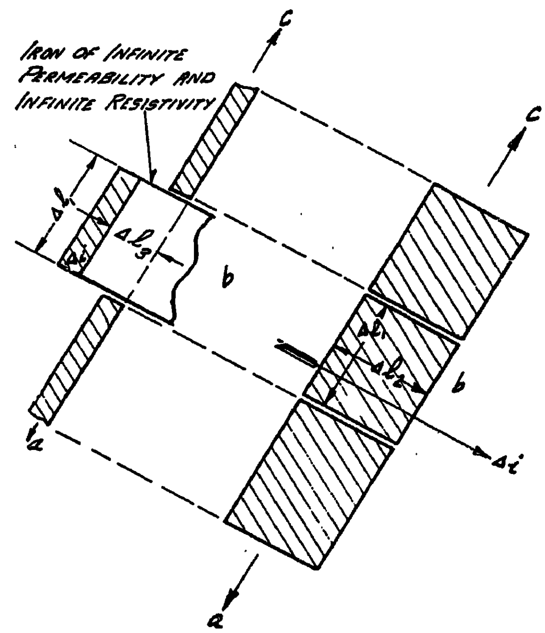


Fig. 22A—A Part of the Current Sheet a-b-c of Fig. 21A

In Fig. 22B the ampere turn lines are shown arriving from the rectangular conductor and terminating in the sheet. When the small conductor is moved (Fig. 22A) it will be supposed that there is a rectangular iron block behind it whose surfaces coincide with the

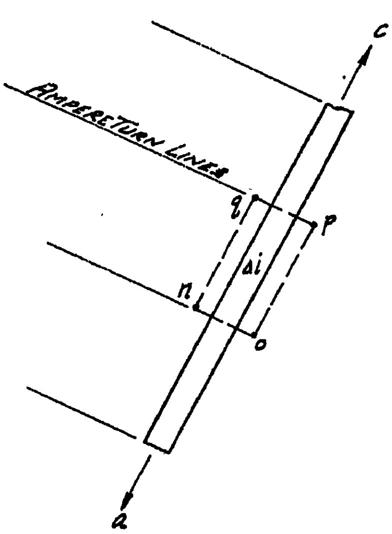


Fig. 22B—Another View of Fig. 22A

ampere turn lines. Work is done on the small conductor, but not on the iron block, because the latter moves perpendicular to the flux and has the same intensities at one surface as on the opposite. The change in stored energy in the whole field is

$$\Delta w' = -\frac{1}{20}\Delta i\,(\Delta \phi) \tag{41}$$

Where Δi is the current in the small element and $\Delta \phi$ the flux which passes through the iron block. This flux has the same magnitude as that which occupied this space before the movement of the small conductor and iron block.

but

$$\Delta \phi = H'\,(\Delta l_3')\,(\Delta l_2') \tag{42}$$

and

$$\Delta w' = \Delta F'\,(\Delta l_3') \tag{43}$$

$$\Delta F' = -\frac{H'\,(\Delta l_2')\,(\Delta i)}{20} \tag{44}$$

where

w' = energy in ergs

$\Delta \phi$ = number flux lines cut through (measured in maxwells.)

$\Delta l_1'$ = length of conducting sheet in the direction of the flux lines.

$\Delta l_2'$ = length of conductor in the direction of current flow.

$\Delta l_3'$ = distance the conductor $\Delta l_1' \times \Delta l_2'$ is moved inward perpendicular to the ampere turn lines.

H' = field intensity near the conductor.

Δi = current flowing in the element of the sheet.

$\Delta F'$ = force acting on the small conductor (measured in dynes).

If a unit pole is moved around the path $o\,p\,q\,n$ in Fig. 22B linking the current Δi, the work done is all along the line $q\,r$ or $\Delta l_1'$ because in this figure H' is zero outside the current sheet.

$$H'\,(\Delta l_1') = .4\,\pi\,(\Delta i) \tag{45}$$

Substituting the value for Δi in that obtained for $\Delta F'$ and rearranging

$$\frac{\Delta F'}{(\Delta l_1')\,(\Delta l_2')} = -\frac{(H')^2}{8\,\pi} \tag{46}$$

which is the force per sq. cm. Converting this to the force in lb. per sq. in. and lines per sq. in.

$$F = -\,0.0139\left(\frac{H}{1000}\right)^2 \tag{47}$$

The above force is one of repulsion tending to force the current sheet outward. The weaker field is on the outside (see the complete Fig. 21A).

The force on the iron surfaces $c - d$ and $f - a$ must be ones of attraction inward and the force per unit area is

$$F = +\,0.0139\left(\frac{H}{1000}\right)^2 \tag{48}$$

(Because this is commonly proved and given in handbooks for use in magnet calculations no proof is given here).

The same arguments as given above for the conductor which contained an m. m. f. center (Fig. 21A) may be applied to the conductor which had no m. m. f. center (Fig. 21B).

It must be remembered that the force on the rectangular conductors which is really sought is equal and opposite to the integral of the force taken over the

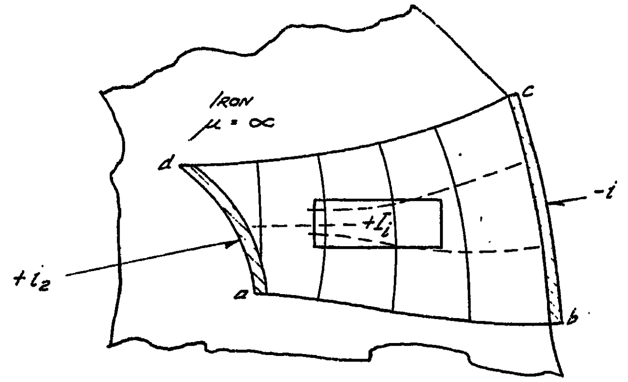


FIG. 23A—SIMILAR TO FIG. 21B BUT WITH ONE BOUNDARY NOT ALONG EITHER PART OF THE ORTHOGONAL SYSTEM

imaginary bounding materials introduced in Figs. 21A and 21B.

It is worth noticing that any section of a magnetic field may be given new boundary conditions without changing the enclosed flux field. It is not necessary to restrict the chosen boundary to either one or the other part of the orthogonal system as was done above. For instance, suppose that Fig. 20B were changed as shown in Fig. 23A. The new current sheet $d - a'$

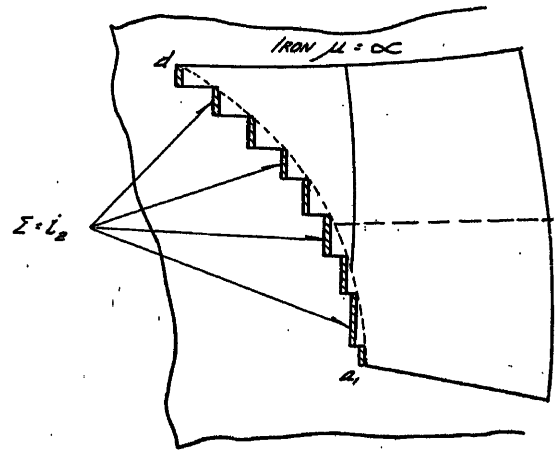


FIG. 23B—THE NEW BOUNDARY $d - a'$ OF FIG. 23A RESC... INTO THE CUSTOMARY ORTHOGONAL COMPONENTS

has just the right density and the iron body is brought up behind it.

It might be imagined that this new boundary is composed of a large number of steps (Fig. 23B), the surfaces of which lie either parallel to the flux or to the ampere turn surfaces. To obtain the resultant force on a small section, it is only necessary to compute

the two components of force indicated in the latter figure.

Appendix E

Limiting Conditions

A serious attempt was made to gain a view of the forces exerted on the entire phase group by mapping fields for certain limiting conditions. The distribution of the ampere turn surfaces on the retaining ring were

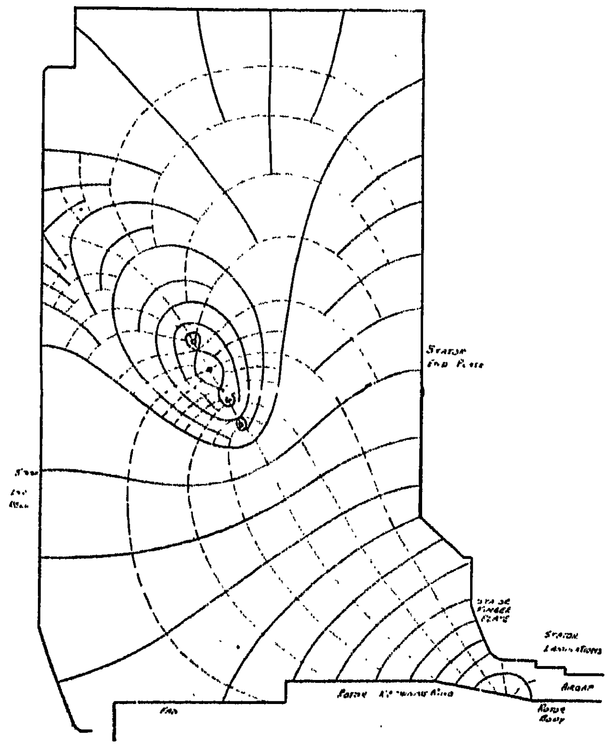


Fig. 24

approximated at the center line between poles. The two layers of armature conductors in this radial plane were plotted as one layer since only the force on the entire group was desired. The fields were plotted as though they were two dimensional, because this had given fairly good results when compared with compass readings on stationary flux fields in this end zone. It was recognized that the stator and end-bell were neither perfect magnetic nor perfect damper surfaces; but the field was plotted (Fig. 24) as though it were the first, and then (Fig. 25) as though it were the second. These both indicate that the winding at its outer edge would have a force component toward the frame.

Aside from approximations necessary to plot these fields, it was felt that the omission entirely of the power component of the damping currents on the bell and frame might be a fallacy which would completely nullify the value of any quantitative results. However, this method will probably have merits in parts of machines where the currents travel either only axially or only tangentially, and these two figures are submitted for this reason, and because they do give a partial picture of conditions in the end zones.

List of Symbols

FLUX, FIELD INTENSITY, AND RELUCTANCE

ϕ = flux in maxwells
${}_a\phi_l$ = armature leakage flux per pole
${}_f\phi_l$ = field leakage flux per pole
${}_a\phi_g$ = air gap flux per pole
ϕ_r = retaining ring leakage flux
ϕ_{si} = leakage flux entering the retaining ring from the under side
H' = field intensity (lines per square cm.)
H = field intensity (lines per square inch)
R = reluctance

CURRENTS (all in practical amperes)

I_a = r. m. s. value of armature current per conductor at normal load
I_2 = maximum possible armature current in upper conductor in a slot on short circuit
I_n = current in an imaged conductor
I_f = field current per slot at some particular instant following a short circuit
i = current in some current sheet
i_{so} = current on the rotor surface and retaining ring surface near the air gap

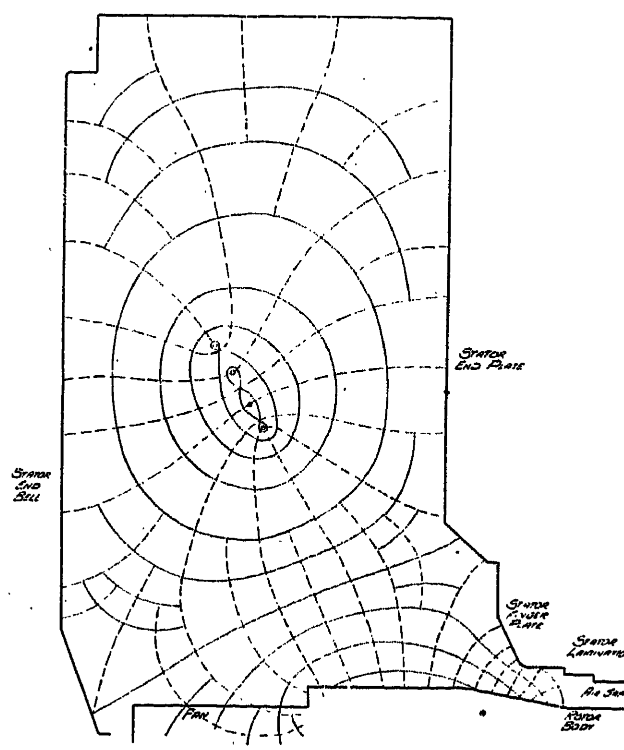


Fig. 25

i_r = component of retaining ring current flowing to oppose change in ϕ_r
i_{si} = retaining ring current on the inside surfaces flowing to oppose change in ϕ_{si}

Inductances and Reactances

(All inductances in practical henrys per in. of length along the conductor)

L_1 & L_2 = self inductances of circuits 1 and 2, respectively.

M = mutual inductance of the same circuits.

X_d'' = subtransient reactance expressed as a decimal.

FORCE, ENERGY, AND POWER

F' = force in dynes per cm. of length and also per sq. cm.

F = force in lb. per in. of length and also per sq. in.

w' = energy ergs.

AXES AND DIMENSIONS

x = distance measured across a slot, or across a conductor in the end winding in the same direction with respect to the strands.

y = distance measured radially inward in a slot, or in the same direction with respect to a conductor at any points.

a = distance between conductors.

s = a surface in air surrounding a conductor.

A_1 & A_2 = cross-sectional areas taken in current carrying conductors.

S_w = slot width.

q = slot pitch.

l = length as defined at the place used.

Δd = width of an incremental flux tube.

N = number of coil sides per phase group.

N_1 & N_2 = number of turns per coil side-in coil 1 and coil 2, respectively.

GENERAL

Where primes are used as F', y', w', H', L', and M', dynes, centimeters, ergs, lines per square cm. and henrys per cm. of conductor are intended.

Where they are not used as F, y, H, then lb., in., and lines per square in. are intended.

Where subscripts as ${}_1F_y$, ${}_2F_y$, are used, forces in the y direction on coil 1 and coil 2 are meant.

Subscript m, as in ϕ_m, indicates mutual flux.

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Discussion

J. A. Terry: Of the three methods employed to determine the magnitude of the forces, the second one, based upon the rate of change in interlinkages, is the one most commonly used. The reason for this is the simplicity with which the desired result can be obtained from the inductance of a system, which of course must be quite accurately known in order that the operating characteristics of a machine may be understood. Thus the forces on the end projections of alternator windings neglecting the effect of the induced rotor currents may be obtained by use of the reactance formulas presented by Mr. P. L. Alger in an Institute paper (1928) *The Calculation of the Armature Reactance of Synchronous Machines.*

The inclusion of the effect of saturation on the forces between the coils is a good contribution to the knowledge of the subject since, in general, saturation materially complicates analyses, and nearly always requires the free use of approximations which can only be justified after the solution is obtained by comparing the resulting flux densities with those which would result from the magnetomotive force obtained in the solution. There is one important point which Mr. Calvert might have mentioned in connection with the comparison between the forces with and without saturation. The comparison has shown that, on the basis of the same slot current in both cases there is a total of 1416 lb. per in. length, neglecting saturation, and 905 lb. per in. length including saturation. As a matter of fact saturation materially reduces the reactance of the machine and thus increases the current flowing during a short circuit so that the comparison on the basis of the same current in both cases does not present the true effect of saturation. Tests have shown that the commercial turbine alternators saturation may decrease the reactance which limits the short-circuit currents to 0.6 of the unsaturated value. If this new current were then substituted in the force expressions the force would be $(1.6)^2 \times 905$ or 2300 lb. However, the saturation for such a current would be greater than for the assumed current so this force is fortunately not correct. It appears offhand that, depending upon the location and degree of saturation, the forces in case of a short circuit might be either greater or less than in the unsaturated case.

In Appendix A a more accurate formula for the line-to-neutral short-circuit current which consists of replacing x_d'' by $\dfrac{x_d'' + x_2 + x_o}{3}$ might just as well have been given; x_2 and x_o are the negative- and zero- sequence reactances respectively. This will give a slightly higher short-circuit current in most commercial machines.

Since the repulsive forces between the coil sides of a slot is of interest in the design of slot wedges it is of interest to study these for some typical cases. Consider that the currents in the upper and lower coil sides are numercially equal but out of phase by an

angle θ in time. The force between the two coil sides will be proportional to $I^2 \left[\sin^2 w\,t - 2\cos^2\frac{\theta}{2}\sin\left(2\,w\,t + \frac{\theta}{2}\right)\right]$ or a maximum when

$$\sin 2\,w\,t = 2\cos\frac{\theta}{2}\sin\left(2\,w\,t + \frac{\theta}{2}\right)$$

The following tabulation gives the relative magnitude of the forces and the instants at which they are greatest:

Condition	θ deg.	Max. repulsive force occurs when $w\,t$ is	Relative values of max. repulsive force are	Relative values of max. attractive force are
Full pitch	0	0 deg.	0	3
Three phase, 2/3 pitch	60	−47.6 deg	0.407	
Two phase, 1/2 pitch	90	−62.6 deg	0.605	
Three phase, 1/3 pitch	120	−75 deg	0.864	
0 pitch	180	−90 deg	1.00	0

Calculations for a number of slow speed machines have shown that the slot wedges generally used are many times as strong as would be required for repulsive magnetic forces only.

B. L. Robertson: The subject of mechanical forces between electric circuits has been treated in a theoretical manner in several papers which have previously been presented, and the study has also been made of the short-circuit forces existing in reactors and transformers. However, the subject of mechanical forces between coil sides of rotating apparatus when abnormal currents are flowing has received little, if any, attention. The present paper therefore becomes valuable because of its attack on this problem, and because the treatment gives quantitative results.

Of general comment is the fact that flux plotting, or magnetic field mapping, has been resorted to throughout the paper. It forms the only basis of solution to the question of forces when one goes just beyond the realm of very simple configurations of iron and copper. This statement readily becomes apparent as soon as the case of saturation enters the picture, or in treating the regions about the coil ends and the end bells. Magnetic field mapping, done either graphically or analytically, has become of practical importance and this is one more illustration of that fact. The industries, however, are the only ones who have as yet done much with it. It is treated to any extent only in a few of the engineering schools of this country, and it is feared that in many institutions it is not even given passing mention.

In such problems as given in the paper, an average condition of operation cannot well be assumed. Hence it is necessary to determine the maximum forces which may exist. Nature is sometimes just so perverse that if the worst condition were not accounted for in design, it would surely be met in operation. The maximum force calculated is 1,416 lb. per in. length of conductor and has been obtained for that case involving all unfavorable influences. At such high values of current as those with which the paper treats, or really for all those cases in which the short-circuit current is many times the normal value, it is shown that saturation is appreciable and should not be neglected. The inclusion of it in the analytical work yields results not quite so pessimistic, as pointed out, when only one value of current is considered.

Because of the fact that saturation is so pronounced, it clearly indicates the importance of knowing in a quantitative way just what it does under other circumstances in which it may have a significant magnitude. Saturation, of course, is always recognized as influencing the results obtained on the basis of no saturation, but is seldom assigned any value. The paper illustrates one case in which its effect is calculable, and as mentioned above, the result has come through field mapping.

It is interesting to note that the interpretation of equation (8) of the paper shows that the value of y is immaterial just so long as it is finite. The radial forces toward the tops or bottoms of the slots are not dependent upon conductor spacing in a vertical direction. This fact could also be reasoned out from Fig. 4 with its symmetry of current carrying conductors and their images.

It is an experimental fact that two conductors carrying current when placed parallel with each other exert such a force action upon each other that they tend to draw together unless constrained. The local flux fields between the conductors are thought of as wiping each other out, leaving a field which encircles both conductors as a unit. The same fact may be shown to be true with many conductors carrying current in the same direction and placed mutually parallel.

This is exactly the situation met in any coil side, and since the condition does not exist that the current in some of the strands is reversed to that in others (skin effect excluded), the resultant force is always one of contraction upon the bundle of conductors. It makes no difference as to the direction of the current flow. For any coil side taken singly, the force will always be toward the bottom of the slot, as can be deduced from the treatment of images, since the conductors and images act as a larger bundle of conductors with currents flowing in the same direction.

The physical fact just stated is experimental proof of conclusion (4), concerning the forces on conductors in armature slots, that the coil sides have no disrupting forces within them. It can also be used to verify the results, shown by Equations (9) and (10), that the force on the upper coil side is greater than that on the lower one. Conductors situated farther from the center of the coil are in a stronger field, and assuming equal current densities in the strands, the force action upon them is greater. The observed fact that parallel conductors carrying currents in opposite directions have a mutual force tending to separate them leads to conclusion (3) of that same group.

I would like to point out that the calculations made by Mr. Terry and myself in our paper on *Analytical Determination of Magnetic Fields* show that the assumption that flux went straight across the slot applies only to total slot flux, or to slot inductance. It is not true when near the kernel, and if that region is to be investigated, the approximate method of assuming straight flux lines cannot be used. That paper also determined by the analytical method that a m. m. f.-center does not exist in every current carrying conductor. This had previously been shown by Calvert and Harrison in a graphical treatment, and is stated in Appendix D of the above paper.

The paper furnishes the start on further quantitative information concerning short-circuit forces on armature coils, and results of the investigation should lead to better or more economical methods of coil bracing, spacing, and wedging. The general treatment also has an application to revolving armature machines in which centrifugal force on the coils is fairly great and must be considered together with the forces due to currents.

L. A. Kilgore: Due to their inherent low reactance turbine generators have always been subjected to strong forces in the end windings on short circuit. As a result of experience methods of very securely bracing the end windings of these machines have been devised. However, the development of an accurate thorough method of calculating these forces is very timely, because the increased ratings and special designs which are now being considered will make demands on the bracing of end windings exceeding the limits of any past experience.

Salient-pole machines in general do not present as difficult a problem as turbine generators, due to their inherently higher reactance. A large part of the method developed here can be applied directly to salient-pole machines. The forces on conductors in the slot and within the conical surface of the end winding are calculated in the same way for both salient-pole and turbine generators.

The forces on the straight section of the end winding are

relatively lower in salient-pole machines because even though the damper winding may project out part way under the end winding, there are no bars between poles where they would be most effective in producing force on the straight section of the end winding.

J. F. Calvert: In reply to the discussion by Mr. Terry: It is true that the change of inductance with displacement is one of the most commonly used methods for computing forces. However, not only the total inductance must be known, but also the rate of change of inductance with displacement. Thus, in the diamond portion of the end winding, it is hardly possible to use Mr. Alger's reactance formulas for the following reasons:

While these formulas probably give sufficiently accurate values for the total flux linkage in this zone, they are built on the assumption that the coils lie in a plane, and that the resultant flux field is symmetrically distributed with respect to this plane. The same argument may be applied here as was used in the paper to compute the tangential force on the conductors in slots. If the coil side is moved a small distance in either of the directions in which the flux field is symmetrical with respect to its initial position, the same change of interlinkage occurs with displacement in one direction as occurs with an equal displacement in the other direction. As the interlinkage of the coil is a single valued and continuous function of the position of the coil, then the rate of change of interlinkage at the initial position is zero. Hence, the force is zero. However, this is not true, as has been amply demonstrated on tests to destruction.

This simply means that while the total interlinkage as given by these reactance formulas may be very nearly correct, and give good results for this purpose to which they were designed, they do not assume the strictly correct distribution of flux, and hence will hardly furnish a means for correctly computing the forces.

In computing the forces on the portion of the armature coils which projects straight out over the retaining rings, the induced rotor currents cannot be neglected. This is particularly true if a good metallic contact exists between the retaining ring and the rotor body. In this case, the rotor surface currents are among the most important factors.

It is stated in the paper that the currents used to compute the forces on conductors in slots (see caption of Fig. 10) are approximately those measured in actual test. Hence, the change in reactance is not involved. It is only necessary to consider the reduction in flux due to the saturation in the iron, as is done in the paper.

The author is in agreement that the more theoretically correct expression for reactance might just as well have been used in Appendix A. Of course, in any case, the proper consideration of saturation is a most important factor. The effects of saturation on a single-phase line-to-neutral short circuit are different from those encountered on a single-phase line-to-line short circuit. The reactance used must be adjusted to take care of this. The most nearly correct value of current is necessary in computing forces.

The instants at which the forces are maximum due to out of phase currents is an interesting contribution. However, slow speed machines are not the ones in which to expect appreciable forces on the wedges. It is in the low-reactance high current per slot (or, in general, high-speed) generators in which this force should be given consideration.

The author is in practical agreement with the discussions of Mr. Robertson and Mr. Kilgore, and is indebted to them and to Mr. Terry for additions to the subject matter of the paper contributed through their discussions.

75-Kv. Submarine Cable for Deepwater Station

BY R. W. WILBRAHAM[1]

Member, A. I. E. E.

Synopsis.—This paper describes the problems attending the laying of eight 75-kv. submarine cables across the Delaware River in the vicinity of Wilmington.

To insure against injury the cables were laid in a backfilled trench, the depth of which was determined from experiments.

By terminating the cable on platforms just inside the pierhead lines it was possible to use a cable of 4,050 ft. (maximum length one of the accepted manufacturers could make) as compared with a river width of 5,100 ft.

To avoid excessive heating of that portion of the cable out of water at the cable platforms, the steel armor was replaced by one of non-magnetic material so designed to avoid corrosion and electrolysis.

The problem of laying the limited lengths of cable in the trench with minimum deviation was satisfactorily met with specially developed methods.

The construction work was completed in five months under winter conditions and heavy river traffic.

* * * * *

THE location of the Deepwater Generating Station on the New Jersey side of the Delaware River, opposite Wilmington and four miles south of Pennsgrove, made it necessary to transmit across the river a portion of the energy to supply the Wilmington and Philadelphia districts.

An overhead wire crossing was proposed, but refused by the United States Government as a potential hazard to aerial navigation. This made it necessary to consider a submarine cable and a study of this problem developed a number of controlling factors as follows:

1. It was desirable to use 66 kv. cable, but the longest piece obtainable was 3,600 ft. as compared with a width of 5,100 ft. of the nearby narrowest part of the river.
2. Pierhead lines had been established on both sides of the river thus extending riparian rights of land owners beyond the shore line, with consequent rights to dredge to a 35-ft. depth or erect structures thereon.
3. All unused land at this narrowest part of the river on the Delaware side was owned by one person who refused to sell and, in Delaware, a power company has not the right of eminent domain. This very greatly limited the possible location for a cable crossing.
4. This part of the river, below Philadelphia, League Island Navy Yard, Chester and Wilmington, has considerable traffic. It is also a natural deep water basin in which ships anchor in fogs or storms; frequently dragging their anchors as attested by interruptions to cables already laid on the bottom.

The solution of the right-of-way problem, and therefore the location of the crossing, was happily reached by the cooperation of the Reading Company which owned the riparian and upland rights on the Delaware side. Rights-of-way on this property were granted by the Reading Company and further inland by the Pennsylvania Railroad for aerial lines (Figs. 1 and 2).

CABLE

Analysis of the cable problem indicated the probability of successful operation of a circuit at 66,000 volts, which was desirable from the point of view of construction, operation, and economy.

The first and most important step was to obtain an agreement by the manufacturers to increase the size of their factory equipment in order to make a cable of sufficient length. By terminating the cable on platforms just inside the pierhead lines it was possible to use a cable of 4,050 ft. which was the maximum length one of the accepted manufacturers could make.

The selected cable was rated at 75 kv. (between conductors), to be used on a nominal 66-kv., three-phase, 60-cycle system with solidly grounded neutral. Eight single conductor cables were so arranged as to make up two three-phase circuits with a spare conductor for each.

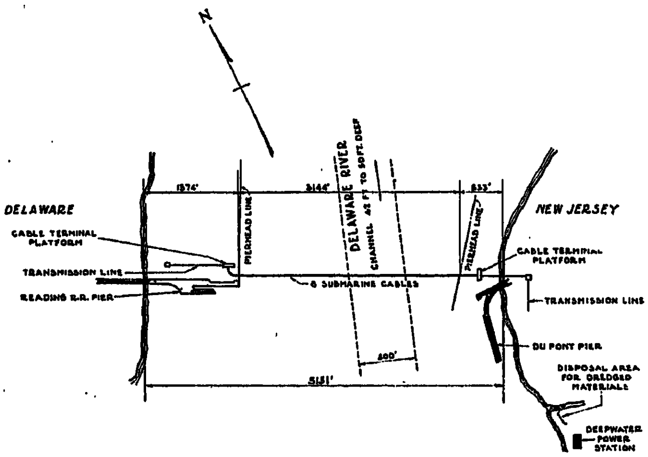

FIG. 1—PLAN SUBMARINE CABLES

The cable is of the single conductor type, paper insulated, electrostatically shielded, lead covered and steel armored. The conductor is of the standard stranded type (not hollow core), 750,000 cir. mils in area. The insulation is 54/64 in. thick, over which is applied a perforated shielding tape. The lead is 5/32 in. thick, covered with two layers of asphalt saturated jute and one layer of No. 4 galvanized steel wire armor, giving an over-all diameter of 3¾ in. and a weight of 21 lb. per ft.

The cable was made according to the specifications of

1. Electrical Engineer, United Engineers & Constructors, Inc., Philadelphia, Pa.

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the Association of Edison Illuminating Companies with certain minor modifications.

Each circuit was designed to carry 60,000 kv-a. continuously (525 amperes per conductor) with a resulting conductor temperature not to exceed 60 deg. cent. This rating was determined on an "in air" basis without steel armor, because it operates in air for an appreciable distance above the water at terminal points.

A comparison of the difference in the losses and first costs for bronze and steel armor was decidedly in favor of the steel and, accordingly, steel was used. There

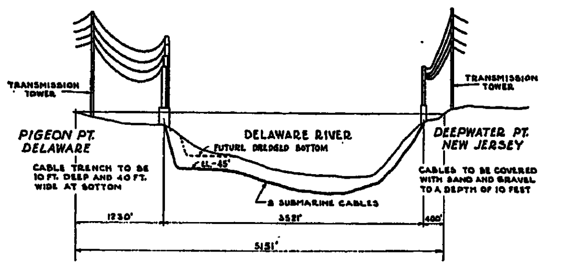

FIG. 2—SECTION SUBMARINE CABLE

would be increased heating from the steel but this was inconsequential for the major part of the cable which was immersed. However, for the short section out of the water, between the river level and the cable potheads, additional heating due to steel was prohibitive. This difficulty could easily be met by removing the steel but the protection of the lead sheath against mechanical injury developed a chain of very perplexing problems involving electrolysis, corrosion, and adaptability.

Due to the fact that the immersed cable would not exceed 40 deg. cent. it was not deemed necessary to include pressure compensating provisions in the cable makeup.

The sheath and armor losses are of particular interest. The manufacturers' computed values for spacings varying from 2 to 6 ft. and for cables in air ranged from 12.5 to 15 watts per ft. The test values of the cable in place on an average of 4 ft. spacing amounted to 10 watts per ft. This may be explained in part by the fact that the submerged cables are subjected to an envelope of brackish conducting water, the effects of which could not be taken into account in the calculations. The dielectric loss was very small, being about one-third watt per ft. at 75 kv. and a copper temperature of 40 deg. cent.

Due to the importance of the installation and the question of the respective merits of the various products, one circuit and spare cable was purchased from each of two manufacturers. The cable was manufactured in eight lengths (each length complete without splices) and wound on reels, having a total weight of 46 tons each. Each piece was 4,050 ft. long from which approximately 125 ft. was taken for test purposes, leaving a net length of 3,925 ft.

The cables were terminated in potheads of the 110-kv. outdoor porcelain type, oil filled design, so constructed as to provide ample expansion of the copper conductor apart from any other portion of the cable.

The standard pothead design was slightly modified by replacing the usual glass oil reservoir at the top by one of all metal oil tight construction. A six gallon oil reservoir under a pressure of seven lb. was connected to the cable immediately below the pothead to insure against the running of the cable compound and voiding the insulation, particularly the portion emerging from the river.

These cable potheads were mounted on the terminal platforms (Fig. 3) which also supported the transmission line dead-end towers, a structure for the operation of the spare cables and bus, a small gantry crane and a deck house for telephone and repair equipment.

MECHANICAL PROTECTION OF THE CABLE

Cables previously laid near the proposed location were subjected to excessive service interruptions due to vessel anchors dragging across them. For this reason it seemed advisable either to lay the proposed cables on the river bed, and provide protection against dragging anchors, or to bury them under the river bed to a depth where they would not be disturbed.

Marine authorities were consulted as to the action and penetration of dragging anchors, but not even fairly accurate information was available. Therefore, it was decided to conduct a series of experiments, based on two methods of protection:

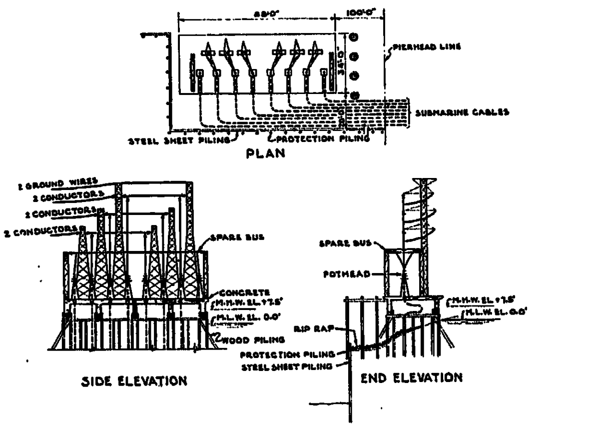

FIG. 3—CABLE TERMINAL PLATFORM

1. Placing the cable in an excavated and backfilled trench at a depth greater than anchor penetration.

2. Cables laid directly on the bottom between two rows of steel sheet piling flush with the river bottom.

Anchors of the stockless type as used on various sizes of vessels were used strictly in accord with marine practise.

Tests in deep water by soundings and in shallow water by observation clearly indicated that an anchor, either dropped or dragged, will not penetrate deeper than its flukes. It was found that sheet piling placed in rows to protect the cables from the anchors was not

effective since the flukes, after engaging the sheet piling, would slip and jump the piling into the cable area and "hook" the cable. These experiments showed that the dragging of anchors was a real menace to the cables; that anchors, except possibly under extraordinary conditions, could not penetrate greater than their flukes or 8½ ft. for the largest anchors normally used, and that the placing of sheet piling in rows was not effective. Therefore, it was decided to install the cables in a trench 10 ft. deep and 40 ft. wide at the bottom and to backfill it to approximately the original level.

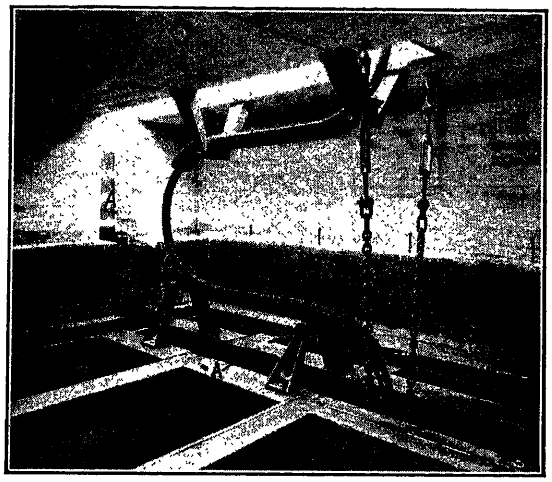

FIG. 4—SPARE CABLE SUPPORT AND SLOTS

Simultaneous with the above experiments, test borings in the river bottom were obtained which showed very unsatisfactory conditions. Three-fourths of the river width from the Delaware side had a plastic mud bottom. This mud was so soft that at times the 4 in. bore casing hung free in the chains 25 ft. below the river bottom. The remainder of the river bottom is firm sand and gravel. This exploration gave rise to the question of whether or not a trench could be dredged and how long it could be maintained open for cable laying. Therefore, further experiments were conducted as follows:

1. Dredging test trenches in mud and gravel sections of the river to determine the time that the trench could be maintained open for cable laying.
2. Dredging test trench in the river bottom between rows of sheet piling to ascertain the effectiveness of piling in retaining the slopes and preventing resilting.
3. Handling of the cable laying or derrick boat across the river for determining alinement, method, and accuracy of travel.

Contrary to the conclusions drawn from the test borings, the results indicated that there would be no difficulty in excavating a trench in the mud with a side slope of one and one-half to one and showed practically no evidence of resilting. However, the velocity of the river eroded the sides of the trench into a very long slope, thus tending to form a new river bottom, which, if allowed, would increase the backfill required or decrease the protection. On the New Jersey side the sand and gravel trench sides held up, but "silted in" about as rapidly as the erosion of the side walls in the mud section. Soundings in the test trenches over a short period indicated that the trench in both the mud and gravel would not maintain, in a satisfactory condition, for more than approximately 45 to 50 days, and that unusual efforts would be required to remove and dispose of 205,000 cu. yd. of excavation, and lay the cable in that period.

CABLE TERMINAL PLATFORMS

Since the cable was of insufficient length to reach entirely across the river, it was necessary to build concrete island platforms just inside the pierhead line to carry the cable potheads and other necessary equipment.

From the beginning it was recognized that this structure would have to be constructed with open slots from and through the piling, straight up to the top of the concrete deck, so that the cable could be "rolled" or placed in position without the necessity of "threading" under the piling and up through the platform, shown at *A* on Figs. 3 and 4.

On the Delaware side the space for the cable platform was not only very limited but accompanied with perplexing conditions. The Reading Company coal loading and freight car ferry piers were immediately adjacent, and there was every possibility that they would dredge around the cable platforms to provide a 35-ft. ship basin, which would undermine the platform foundations unless special precautions were taken. Protection was provided by steel sheet piling, flush with the present bottom, acting to confine the foundations. Wood piling, 8 ft. on centers, was driven parallel with the sheet piling to act as a guide or warning for future construction operations of the Reading Company (Figs. 3 and 5).

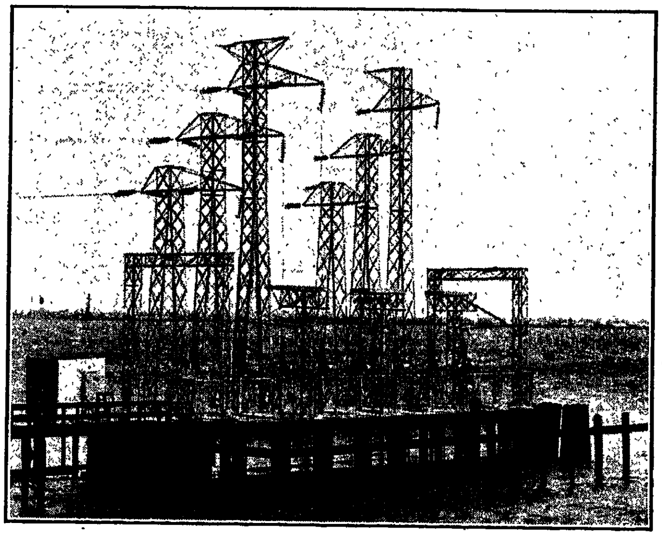

FIG. 5—CABLE TERMINAL PLATFORM

The foundations are of wood piling and timber work, on which the platform proper is carried in the form of a slotted concrete box, setting over corresponding slots in the piling and timber work (Fig. 5). Each platform has four compartments, completely "closed off" with concrete walls, providing structural strength and safety against fire. Each compartment is provided with two slots for two cables and after the cable was installed, the slot was closed with stop logs of such design as to keep out heavy floating debris, but at the same time to provide partial automatic cleansing of the water in the compartment with the changing tides. The platforms are fenced and protected by piling.

The spare cables can be used in any circuit by having each spare cable permanently connected to a spare bus

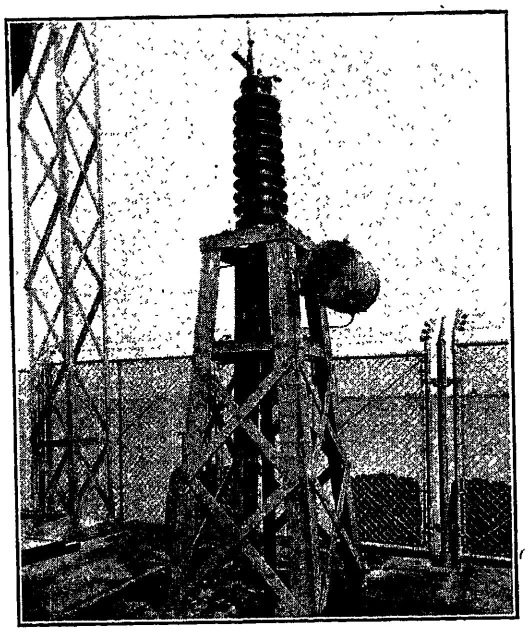

FIG. 6—CABLE TERMINAL AND SUPPORT

and providing removable connectors in the vertical drops to the remaining six cables. In the event of failure of any one cable, its connector in the drop is removed and the upper part of the drop swung over to either spare bus.

The porcelain cable potheads are carried on a tapering four legged latticed steel structure which is fastened to, but completely removable from, the concrete deck (Fig. 6). It is so designed that the latticed work, which normally acts as a protective barrier, can be completely removed, providing complete accessibility to the cable..

A small traveling cantilever type crane is provided to handle the porcelain potheads or other work in connection therewith, and is so designed that it cannot be moved from the storage point to the pothead space without placing the rotating boom in such a position as to avoid conflict with live risers of other cables.

To comply with the heating conditions of the specifications, the armor was removed from that part of the cable in the air. The steel armor is terminated one foot below low water and lapped around three large cast iron flanges bolted together, which are suspended from the underside of the concrete platform by means of two chains and turnbuckles (Fig. 4), which provide an effective manner of dead ending the steel. To prevent tide action and ship wash from moving the cables where they slope into the cable platform a mat of "rip rap" was laid on the cables from inside the structure to a reasonable distance outside the structure as indicated on Fig. 3.

The exposed cable above the armor is partly in air and water according to the tides, which required all the cable under the platform to be protected against damage from ice and debris. This matter of protection gave rise to an electrolysis and corrosion problem, which is discussed later.

As originally planned, the dead weight of the cable between the armor clamping flanges and the bottom of the pothead (22 ft.) was to have been relieved from the pothead by means of double ear woven wire cable grips, approximately 4 ft. long, suspended inside the pothead support and immediately under the wiping sleeve of the pothead (Fig. 6), but the cable was laid with such accuracy that approximately 190 ft. remained on each side. It was planned to utilize as much as possible of this extra length by providing loops in the cable in the compartments under the deck of the platforms. This was accomplished rather easily, as shown in Fig. 4, by laying the spare cable in two cast iron troughs provided with treated wood shoes, to prevent battery action. This removed all of the dead weight between the armor clamping rings and the underside of the platform, leaving but 9 ft. of cable to the potheads. The use of the cable grips on this short length might be questioned, but they were installed to provide against slippage of the cable in the troughs and resulting possible stresses on the potheads.

Cable grips have been mostly used heretofore for construction purposes only and experimental work was conducted to determine the holding power and distribution of pressure for various lengths of grips. It was found that, with proper selection and weave of material, together with the length and separation of the eyes, that the forces equal to the ultimate strength of the grip could be distributed over the entire length of the grip without injury to the lead sheath.

ELECTROLYSIS PROTECTION

The removal of the steel armor from the cable necessitated the installation of non-magnetic protective armor after the cable was laid and placed in the slots of the platform. This was particularly difficult. Materials had to be selected or placed in such a manner so as not to be affected by the brackish and corrosive river water or set up electrolytic action, and be of such mechanical composition and arrangement that it could be installed in the restricted slot space of 18 in. between the piles and

immediately adjacent to the armor clamping rings, one foot below mean low water. Many methods of accomplishing this were considered and experimented upon, but were found to be weak or practically impossible.

The winding of steel or bronze tape or wire was out of the question as was demonstrated by experiments. Such metals in the presence of river water would set up battery action which, in the case of bronze, would attack the lead and, it was estimated, completely destroy it in approximately seven years. In the case of the steel, the lead would not be attacked but the steel would be subject to electrolysis and the corrosion of the river water, giving it a life not in excess of four to five years. Many other methods of wrapping the lead cable with a waterproof material on which bronze armor could be wrapped was not only questionable as to protective value, but was next to impossible to install due to the limited space.

Finally a method was devised that avoided all of the other difficulties and was extremely simple in every way. This consisted of slipping over the cable a commercial, flexible, liquid tight bronze hose, to each end of which was fastened a coupling. This flexible hose was fastened to the armor clamping rings at the bottom

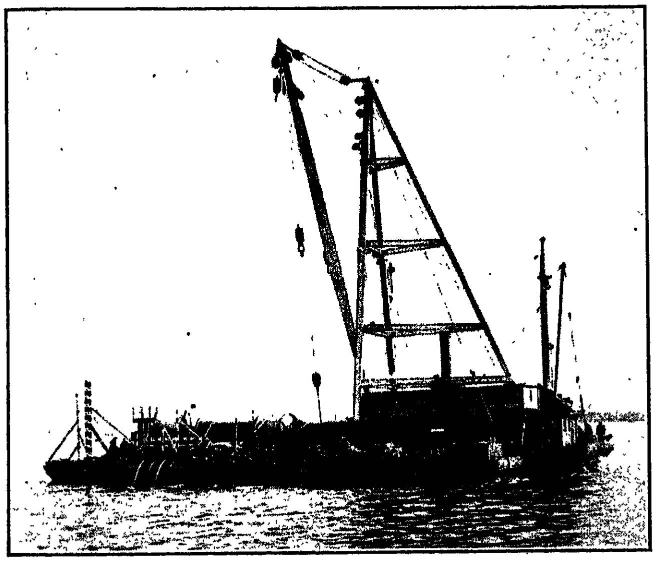

FIG. 7—CABLE LAYING BARGE

and stopped at a point just below the top of the concrete deck. The couplings at each end were made tight against the lead sheath over a lapping of asbestos tape. The hose, being larger than the cable, was filled through a grease fitting in the lower coupling with a neutral grease and oil until it escaped from a relief valve in the top coupling. This has proved to be very successful. The hose is strong and affords every protection against ice and debris. The neutral oil and grease prevents the bronze from coming in contact with the lead and setting up battery action and most effectively keeps out the river water, thus preventing electrolysis.

CONSTRUCTION AND INSTALLATION

The construction work was divided into four operations: dredging, laying cables, backfilling and cable platforms.

The cables were laid as soon as possible after trenching was completed in order to avoid the results of sloughing and resilting of the trench, which was considerably in advance of the completion of the cable platforms.

Trenching was carried on with five dredges operating

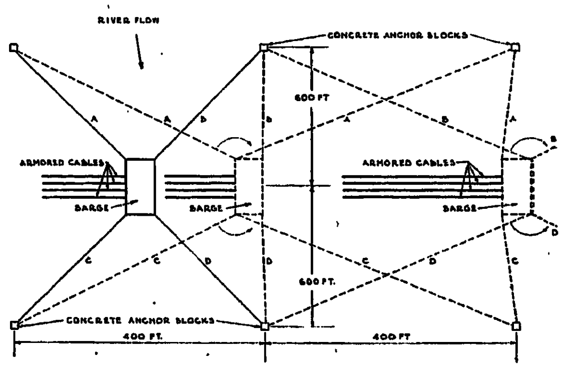

FIG. 8—CABLE BARGE PROPELLING ITSELF ACROSS RIVER

day and night. The trench was approximately 40 ft. wide by 10 ft. deep at a maximum depth of 62 ft. below mean low water and an average of 45 ft. The dredged material was barged down the river to a point in front of the new Deepwater Power Plant where a suction dredge rehandled the material and filled up the low land around the plant. Material to the extent of 205,000 cu. yd. was removed and disposed of in 43 days.

Considerable thought had been given to the handling of the cable laying or derrick boat, particularly to keeping it in as straight a line as possible. In considering this problem it is well to have an idea of the magnitude of this particular part.

The river at ebb tide has a velocity of about 2½ miles per hour, the wind and sleet storms in the fall and winter are severe and at all times the river traffic was annoying and uncomfortably close. It was felt that it was best to lay four cables at a time which gave approximately a 250-ton, reel and attendant equipment load. A derrick of ample capacity had to be available to reclaim cable in the event of the boat getting off course beyond the trench, or the occurrence of an accident. There was but a difference of 209 ft. between the amount on the reels and the actual computed length of cable required, without allowances for deviation. Consequently, the question of keeping the cable boat on a straight course was of outstanding importance.

Experiments were conducted with the equipment intended to be used and it was found that the laying of cables could be best accomplished by placing heavy concrete anchors in the river bed on each side of the cable laying boat, and by means of anchor lines, have the boat pull itself equally between the anchors with

relative safety. The total horizontal deviations in these trials was found to require about 150 ft. of cable, thus leaving the very small spare amount of 59 ft. for unforeseen conditions.

The cables were laid four at a time, two trips being required to complete the operation. The cable reels were mounted on the bow end of a large derrick boat (Fig. 7) which was towed to one end of the trench, immediately adjacent to the cable terminal platform, where the ends of the cables were taken off and placed in position on a temporary rack.

The boat was maintained lengthwise to the flow of the river (Fig. 8) and kept in line over the trench by means of two cables from the bow and two from the stern, fastened to anchors made of 30-ton concrete blocks. These anchors were set in two lines across the river, one line upstream and the other downstream from the trench. The rows of anchors were approximately 1,200 ft. apart, with a spacing of 400 ft. apart in each row. Each anchor had a flexible cable attached to it, terminating in an eyelet above the surface of the water, supported by a spar buoy. The bow and stern lines of the derrick boat were wound on large drums and so connected to an engine drive on the boat that all four drums could be operated in any combination, in synchronism or separately. Thus the derrick boat pulled itself across the river and maintained itself on the established line by the use of ranges and check methods developed especially for this service. As the boat progressed across the river, the bow and stern lines were shifted from one anchor to another as shown in Fig. 8.

As the cables were being laid they were frequently checked by a diver and later by soundings which showed the cables to be 4 ft. apart and practically balanced across the center line of the trench, with a maximum deviation of any cable from a straight line not exceeding 6 ft. The experimental or trial run of this method indicated 150 ft. required for deviations, but in the actual laying only 60 ft. was used.

This was the most important element in the satisfactory completion of the job.

Immediately following the laying, the concrete anchors were removed and the trench backfilled with sand and gravel.

The construction of the cable terminals did not involve difficulties except that, due to the fact that the cables were placed on a temporary structure long before the concrete was poured, more than usual care had to be exercised to prevent injury to them.

The engineering features and the right-of-way were started in the spring of 1929, but nothing conclusive could be done until the right-of-way was determined in August when the work was given a definite beginning and prosecuted vigorously in the face of approaching winter.

The dredging was started October 7, 1929 and finished November 25th. The cable laying was started on November 27th; the first run finished in 5 days and the second in 3½ days. The backfilling and cable platforms were finished on February 14th and March 7, 1930, respectively, and the cables placed in service on March 9, 1930, a total elapsed construction time of 131 days.

This project was constructed for the Delaware Power & Light Company, subsidiary of the United Gas Improvement Company, by United Engineers & Constructors, Inc., and is operated jointly with the Philadelphia Electric Company.

Discussion

R. J. Wiseman: Some facts pertaining to the manufacture of the cables, the construction of which is given in the paper, on account of being the longest lengths of 75-kv. cable ever made in the world and the first extra high-voltage submarine cable are given in the following discussion.

A jute serving which held the armor wires snugly in place while installing was wrapped for 50 ft. on each end. We believe that submarine cables should have a jute serving throughout their entire length. Also, we thoroughly slushed the armor wires during the armoring process in order to reduce armor losses.

The order called for four 4,050-ft. lengths of cable. Four 4,115-ft. lengths were manufactured. The tank equipment used for drying and impregnating was especially designed to take care of extra long lengths of cable. The impregnating reel had a 17-ft. traverse and weighed 14,000 lb. It is capable of handling 6,000 ft. of cable of this size in one piece. Our standard impregnating reel will handle a 1,700-ft. length of this cable which weighs 3,800 lb.

The cables were shipped on the impregnating reels, so designing them to be used for both purposes. The total weight of reel and cable as shipped was 48 tons. Special shafts and pedestals had to be designed and built to take care of this weight. A special yoke which weighs three tons was designed and built to lift the loaded reel. This equipment was loaned to the purchaser in order to transfer cables from railroad car to barge and setting up on barge. On shipment we very carefully housed in the reel to prevent any damage during shipment.

Each reel of cable took 54 hr. to dry, 130 hr. to impregnate, 20 hr. to lead and 32 hr. to armor. There were 39,000 lb. of copper, 56,000 lb. of paper and oil, 116,000 lb. of lead and 115,000 lb. of armor wire required for this order. The dielectric loss averaged 0.35 watts per ft. at 40 deg. cent. and 0.50 watts per ft. at 60 deg. cent.

Tests on the installed cable show that with a 560-ampere load, the temperature rise was 29 deg. cent. On this basis and assuming an ambient temperature of 15 deg. cent., the permissible load for the under-water section would be 700 amperes. However, the maximum load on account of terminal conditions is no more than about 560 amperes.

The armor and sheath losses were estimated at about 14 watts per ft., but actual tests showed for a 560-ampere load, about 10 watts per ft.

The cables have come up to our expectations in every way and we have full confidence in them to perform as intended. We feel that both the United Engineers & Constructors and the Philadelphia Electric Company are to be congratulated in their very thorough study of the whole problem, the painstaking care exercised during installation and the courage to be a pioneer in extra high-voltage submarine cables. We are very thankful to them for the opportunity to furnish one circuit.

R. W. Atkinson: The measurements of effective resistance upon these cables have resulted in a very satisfactory check on an exceedingly simple method of calculation of sheath and armor losses for this type of cable. Preliminary calculations showed

that the combined current in the lead sheath and armor would approximate rather closely to the current flowing in the conductor and that wide variations in assumptions would affect only slightly the calculated amount of this circulating current. Further calculations made to determine the probable amount of the magnetic losses with both armor and sheath short-circuited, and also of the loss produced by circumferential flow of current in the lead sheath caused by the spiralling of the armor wires, showed these to be negligible. Determination of losses was therefore made on the following basis. The combined sheath and armor current was assumed to be equal to the conductor current and assumed to be divided between the armor and sheath in proportion to the relative a-c. conductance. Based on a conductor current of 525 amperes, calculations by this method gave a total sheath and armor loss of 12 watts per ft. which was the value given by our company. The agreement with the measured value of 10 watts per ft. given in Mr. Wilbraham's paper is surprisingly close.

This installation marks a distinct advance in the use of submarine power cables. The proposition had been under consideration for a number of years and the general impression had been that the installation of such cables would be extremely difficult if not actually hazardous. The preparations for the job as described in Mr. Wilbraham's paper, however, were so complete and thoroughgoing, that the solutions of all the problems involved were ready in advance and the actual installation was accomplished with no greater difficulty than attends normal submarine installation.

From the manufacturing standpoint, most of the procedure was exactly the same as for the usual lengths, the main difference being the necessity for providing the necessary huge reels and equipment for handling them. The testing of such a cable, however, presented some unusual and interesting features. The charging current on these lengths at 169,000, the voltage required by standard specifications, is approximately 16 amperes, whereas testing transformers within this voltage range ordinarily have one-ampere secondaries. Thus, the supply of this very high charging current was beyond the range of any ordinary testing equipment even where augmented by the use of several transformers in parallel. There was discussion of testing the cables at a modified or compromise test voltage. It was, however, appreciated that since the result of failures on submarine cables are very much more serious than on underground, any reasons justifying the testing of underground cable at standard test voltages become doubly important for submarine cable. Furthermore, the very fact that even though these cables were different from other cables of regular manufacture only from the standpoint of their unusual length, the mere fact of this one difference from the standard and normal factory procedure made it imperative that no precaution that would normally be considered important for underground cable should be waived for these especially important cables. Since the special apparatus necessary to supply the charging current could not be obtained in time in any other way, this was designed and built by the Research Laboratory and standard tests were made according to the A. E. I. C. Specifications. Thus, in addition to emphasizing the usual careful factory inspections, no part of the assurance obtained by testing on the finished cable normally obtainable on short sections was omitted with these important submarine cables.

J. W. Sylvester: There is little that can be added to the paper except to emphasize several of the unusual problems which presented themselves in connection with its manufacture and its installation.

The manufacturers' problems were, first; to build a cable rated for 75 kv. in such long lengths that it required numerous changes in their factory equipment, second; to provide the electrical testing equipment which would permit the testing of these cables after completion. These problems were solved by the manufacturers as the tests of various kinds which were applied during and subsequent to the manufacture of the cable clearly showed.

The construction company's problems were many, but the two which were outstanding were, first; to excavate a trench across the river at a very unusual depth for river crossings in which it was intended to bury the cables, second; to lay these cables in the trench and in as straight a line as possible.

As so well described, both of these problems were solved in a very satisfactory manner and both the manufacturers and the construction company are to be complimented upon having planned and executed their respective responsibilities so thoroughly.

This installation was the outstanding cable event of 1930. Judging by the extremely careful manner in which every process in the manufacturing of the cable and its installation was carried out, as it was the writer's privilege to view them, these cables should render the service expected of them for many years to come. They are well buried beneath the bed of the river and we believe are out of the reach of ships' anchors or any other disturbing cause likely to result in mechanical injury, which from past experiences has been the bane of most submarine cable installations.

Circuit Breaker Recovery Voltages
Magnitudes and Rates of Rise

BY ROBERT H. PARK* and WILFRED F. SKEATS†
Associate, A. I. E. E. Associate, A. I. E. E.

Synopsis.—This paper shows the conditions affecting the magnitude and rate of rise of recovery voltage at the terminals of an oil circuit breaker upon interruption of a short circuit, and explains their effect in quantitative terms.

Factors are presented whose numerical value takes into account the number of phases involved in the short circuit and the ground connections of short circuit and generator, the decrement of short-circuit current previous to interruption, and the effect of unequal reactances in the direct and quadrature axes of synchronous machines. It is also indicated how to take into account the effect of displacement and of initial load current, and the effect of saturation is discussed very briefly. Magnetic oscillograms are presented which verify the most important of the points brought out.

The most common locations and a rough idea of the magnitude of the capacitances affecting the rate of rise of recovery voltage for various types of short circuit are indicated. Calculations of the recovery voltage curve for several representative cases, at both low and high voltages, are presented, and in some cases cathode ray oscillograms are presented for comparison with the calculated curves.

While no systematic data appear to be available at present regarding the effect of the rate of recovery voltage rise upon circuit breaker operation, several tests showing a very pronounced effect, some of them made by the authors and some by others, are reported briefly.

A discussion of the method by which overvoltages are built up during the interruption of transmission line charging currents is presented at the end of the paper.

* * * * *

INTRODUCTION

WHILE the duty on circuit breakers is commonly expressed in terms of the circuit voltage previous to short circuit, and the magnitude of the current in the arc, it is a matter of experience that in practise other circuit characteristics may affect the duty to an important extent.

For instance, tests made on the system of the Northern States Power Company, at St. Paul, Minn., during the month of September, 1925, brought to light a case of marked difference in the difficulty of opening the circuit, depending on the source of power employed.

This difference was between three-phase tests with breaker neutral ungrounded when connected through a 43-mile, 110-kv. line to an 18,750-kv-a., turbine generator at the Riverside Station; and similar tests when directly connected to three 6,600-kv-a. water-wheel generators at the Wissota Station.

Referring to Table I it will be seen that in spite of the slightly lower voltage, much greater difficulty was encountered when directly connected to the bus at Wissota.

TABLE I

Source of power	Riverside	Wissota
Number of tests made	2	5
R. m. s. line-to-line volts before short circuit	15,000	13,200
Average initial r. m. s. current in the arc	1,400	1,420
Inches of arc	1.2	4.8
Half cycles of arc	3.5	10.0
Maximum pressure, lb./sq. in.	6.5	36.0

Again, tests recently conducted on a 110-kv. (63.5-kv. to ground) explosion chamber breaker showed a marked difference between tests with the standard test circuit of the company with which the authors are associated, and a modification of this circuit in which a shunt resistance of 1,000 ohms was connected across the circuit breaker terminals.

In these tests it was found that without the resistor, the breaker would not clear the circuit at 88 kv. to ground across one pole, while with the resistor 132 kv. to ground across one pole was cleared. Actually the arc length required at 132 kv. with the resistor was less than that required without the resistor at 66 kv.

Also similar effects have been observed to a lesser degree in many other cases.

As a result of studies made at the time of the St. Paul tests, it became evident that these effects could be explained in terms of the brief "kicks" which occur in the recovery voltage and the time delay required for their establishment.

Table II shows data prepared in connection with this study.

TABLE II

Source of power	Riverside	Wissota
Phase voltage before short circuit	12,240	10,780
Phase voltage one cycle after recovery	8,200	7,500
Recovery voltage of phase which opened first		
(a) "abrupt"‡ rise	2,800	13,500
(b) peak	14,600	18,000
Time delay from a to b in milliseconds (as measured on magnetic oscillogram)	1.0	0.8
Peak recovery voltage of phases which opened later	9,100	7,800

It will be seen that at Wissota the kicks were of greater amplitude and were established in a shorter period. The conclusions arrived at in this study were briefly stated by Mr. J. D. Hilliard in his discussion

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‡The only oscillograms available in these tests were of the magnetic type and hence any very high frequency voltages which may have been present would not be observed. Probably such voltages were present in the form of an overshoot to approximately double the "abrupt" value.

of the paper presented in 1927 by Sporn and St. Clair. Since that time Slepian and Biermanns have further emphasized the significance of these factors. Thus the phenomena have been demonstrated and there has been agreement as to the basic conceptions necessary to understand them.

On the other hand, no very comprehensive analysis has been presented, to show how the magnitude and time delay of these kicks of recovery voltage are affected by the various types of apparatus which are found on transmission systems. This paper attempts to present such an analysis with numerical calculations for several of the simpler cases, and magnetic and cathode-ray oscillograms confirming these calculations.

The paper is divided into two parts of which Part I summarizes the conclusions and Part II gives the theoretical work on which the conclusions of Part I are based.

Part I

Summary of Conclusions

The phenomena of recovery voltage may be divided into two parts, low frequency effects and high frequency effects. The low frequency effects comprise those arising from the type of short circuit, decrement, displacement, and flux distribution in rotating machinery, and include most of the factors determining the magnitude of recovery voltage. The high frequency effects are attributable to the capacitances of the various parts of the system to ground. They are responsible for an overshoot, often to double the value predicted from the low frequency considerations, and include all of the factors determining the time required to reach the maximum value. It is convenient to consider these two types of phenomena separately. The low frequency phenomena will be treated first.

Low Frequency or Magnitude Phenomena

A. Nature of the Impedance Limiting the Short-Circuit Current

In a short circuit in which the current is limited principally by resistance, the recovery voltage wave starts near the zero point of the cycle, so that the instantaneous value for the first-thousandth of a second is low. When the current is limited principally by reactance, however, unless the current wave is displaced, the recovery voltage wave starts at its crest value. A reactive short circuit is therefore much more difficult to interrupt than a resistive short circuit of the same current and voltage. Unfortunately practically all serious short circuits are almost purely reactive.

B. Number of Phases Involved and Ground Connection of System; Effects of Stationary Apparatus, No Load

1. *Single-Phase Short Circuits.* Where the short-circuit impedance of stationary apparatus is much greater than that of rotating machinery, for single-phase short circuits, either line-to-ground or line-to-line, the voltage after interruption is the same, except for high frequency effects, as the voltage before establishment of the short circuit. The oscillogram of Fig. 1 shows both voltage and current for a line-to-line short circuit on a 13,200-volt, 26,700-kv-a. generator with 1.5 ohms external reactance in series per line. Voltage both before and after the short circuit are shown and these will be seen to be identical.

2. *Three-Phase Short Circuits.* The general expression for the recovery voltage of the first phase to clear of a three-phase short circuit, where the effect of stationary apparatus predominates, in terms of symmetrical phase sequence components, is

$$e = \frac{3\,E\,Z_0\,Z_2}{Z_1\,Z_2 + Z_0\,Z_1 + Z_0\,Z_2}$$

where E is the phase-to-neutral voltage existing before short circuit.

If either the generator or the short circuit is ungrounded, Z_0 is equal to infinity, and in stationary apparatus $Z_1 = Z_2$. Making these substitutions, for the first phase to clear of an ungrounded three-phase short circuit, or of any three-phase short circuit on an ungrounded system,

$$e = \frac{3}{2}\,E$$

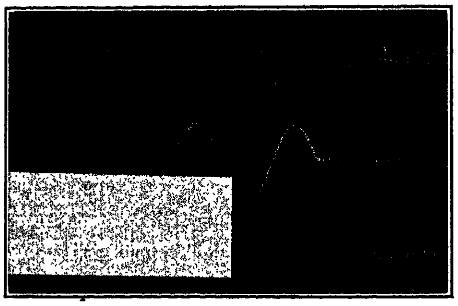

Fig. 1—Oscillographic Record of a Line-to-Line Short Circuit on a 13,200-Volt, 26,700-Kv-A. Generator with 1.5 Ohms External Reactance in Series per Line

Fig. 2 shows an oscillogram taken on the first phase to clear of a three-phase short circuit at 13,200 volts on a 100,000-kv-a. alternator, ungrounded, with reactance in series per phase equal to about ten times generator subtransient reactance.[3] The ratio of the first peak of recovery voltage to the crest voltage existing before short circuit (as determined from a voltmeter) is 1.47.

If both the system and the short circuit are solidly grounded, Z_0 may have a low value and the recovery voltage of the first phase to clear may be very low, or, on the other hand, Z_0 may be equal to or greater than Z_1, and the recovery voltage equal to or greater than the voltage existing before short circuit.

In systems grounded through a neutral impedance, the neutral impedance is usually high enough so that

3. See Bibliography.

the recovery voltage is practically that obtained on an ungrounded system.

If the neutral is grounded through a reactor, this peak voltage occurs immediately (except for "high frequency" delay) upon interruption. If the neutral impedance is a resistor, however, the initial value of recovery voltage is the same as if the neutral were solidly grounded. The voltage then rises more slowly to its peak value, which occurs usually about 10 or 20 deg. after the interruption. A neutral resistor thus possesses a slight advantage over a neutral reactor from this point of view.

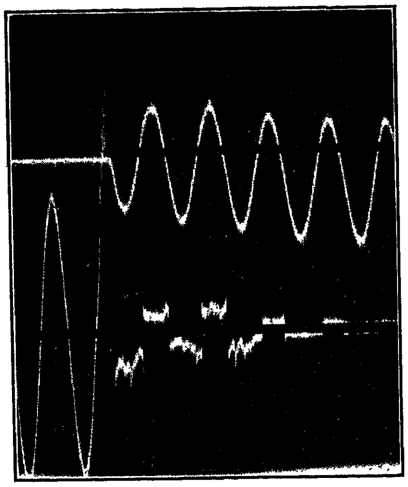

FIG. 2—OSCILLOGRAPHIC RECORD OF CURRENT AND VOLTAGE OF THE FIRST PHASE TO CLEAR OF A THREE-PHASE SHORT CIRCUIT AT 13,200 VOLTS ON A 100,000-KV-A. ALTERNATOR, UNGROUNDED

External reactance per phase ten times generator subtransient reactance

3. Two-phase-to-ground Short Circuits on an Impedance Grounded System. For the first phase to clear of a two-phase-to-ground short circuit, the recovery voltage varies from a theoretical minimum of half line voltage, with negligible zero-phase sequence impedance, to line voltage, with very high neutral impedance, if the neutral impedance has the same phase angle as the line impedance. If the neutral impedance phase angle differs from that of the line impedance, the recovery voltage for one phase is somewhat decreased, while that for the other is increased.

C. Effects Arising From Rotating Machinery at No Load

Fig. 3 represents the decrement of the a-c. component of current through the breaker during a severe three-phase fault. In this figure,

i'' = initial inrush current

i = current at the time of clearing.

The recovery voltage for the first phase to clear of a three-phase short circuit at the machine terminals, if either the machine or the short circuit is ungrounded or has a high ground impedance, is

$$e = 1.5\, x_q''\, i$$

where x_q'' = the quadrature subtransient reactance of the machine.

For a three-phase short circuit at the machine terminals at no load,

$$i'' = \frac{E}{x_d''}$$

where E = the leg voltage of the machine before short circuit, and x_d'' = the direct subtransient reactance of the machine.

Thus the recovery voltage formula may be written

$$e = 1.5\, E \frac{i}{i''} \frac{x_q''}{x_d''}$$

If the short circuit is not at the machine terminals the quantities x_q'' and x_d'' should be replaced by quantities s_q'' and s_d'' where s_q'' and s_d'' are the reactances of the system using, respectively, quadrature and direct subtransient reactances as the reactances of the generators.

The recovery voltage for the first phase to clear of a three-phase short circuit may therefore be considered as the leg voltage of the system before short circuit, modified by three factors:

1. A factor k_g, which depends upon ground connections.
2. A decrement or "change in excitation" factor, k_δ.
3. A quadrature reactance factor, k_q.

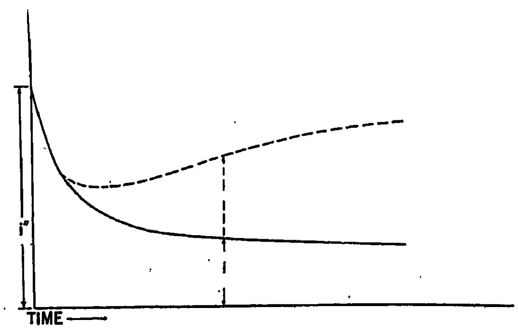

FIG. 3—DECREMENT OF THE A-C. COMPONENT OF CURRENT DURING A SEVERE FAULT

i'' = initial inrush current
i = current at time of clearing
Full line refers to hand-regulated machines, and dotted line to machine with high-speed excitation

The values of k_g, k_δ, and k_q for all types of short circuit are given below:

1. k_g = 1.0 for one-line-to-ground short circuits.

$$k_g = \frac{2\sqrt{3}\,(s_q''^2 + s_q'' x_0 + x_0^2)^{3/2}}{s_d''(2\,s_q'' + x_0)^2 + x_0(2\,s_q'' + x_0)(s_q'' + 2\,x_0)}$$

for two-line-to-ground short circuits.

k_g = 1.73 for line-to-line short circuits or (approximately) for the first phase to clear of two-line-to-ground short circuits on an impedance-grounded or ungrounded system. (In the case of a line-to-line short circuit on any system or a two-line-to-

ground short circuit on an ungrounded system, the voltage usually appears across two poles of the breaker in series.)

$$k_g = \frac{3\,x_0}{s_q'' + 2\,x_0} \text{ for three-phase short circuits.}$$

$k_g = 1.5$ for three-phase ungrounded short circuits or for three-phase grounded short circuits on an ungrounded system.

2. $k_\delta = \dfrac{i}{i''}$ for all short circuits.

3. $k_q = 1.0$ for all single-phase short circuits.
$k_q = 1.0$ for two-line-to-ground short circuits.

$$k_q = \frac{s_q''}{s_d''} \text{ for all three-phase short circuits.}$$

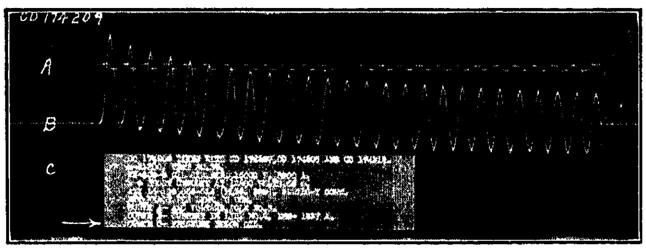

FIG. 4—OSCILLOGRAPHIC RECORD OF CURRENT AND VOLTAGE OF THE FIRST PHASE TO CLEAR OF A THREE-PHASE SHORT CIRCUIT AT 13,200 VOLTS

On a 100,000-kv-a. generator, without an amortisseur winding, operating with the neutral ungrounded. No external reactance

Average values of $\dfrac{x_q''}{x_d''}$ for machines of various types are given by Table III.

TABLE III

QUADRATURE REACTANCE FACTORS

Types of machine	$\frac{x_q''}{x_d''}$
Turbo-alternators	
a. Laminated rotor	2.5
b. Solid rotor	1.4
Salient-pole machines	
a. Without amortisseur	2.3
b. With amortisseur	1.1
Induction motors	1.0

Effect of Amortisseur Winding

Table III shows very strikingly the effect of an amortisseur winding in reducing the quadrature reactance factor of a salient-pole machine, and thus in reducing the recovery voltage of the first phase to clear in short circuits involving more than one phase.

This table indicates a reduction of a little more than 50 per cent in the recovery voltage of the first phase to clear of a three-phase ungrounded short circuit. Actually the reduction may be even more than is indicated by Table III, for the decrement factor is likely to be lower with an amortisseur winding than without. Saturation may modify the effects slightly.

Thus an amortisseur winding brings about a substantial reduction in the duty of a circuit breaker opening a three-phase ungrounded short circuit close to the terminals of a salient-pole machine.

Figs. 4 and 5 show oscillograms of two short-circuit tests on the same machine, that of Fig. 4 being taken before the amortisseur winding was installed on the machine and that of Fig. 5 afterwards. The first peak of recovery voltage is much higher in Fig. 4 than in Fig. 5. A brief quantitative analysis of these films is given in Part II.

D. *Effect of Displacement*

The existence of a large d-c. component in a short-circuit current may cause the recovery voltage wave to start near the zero point instead of at its crest. The instantaneous value of recovery voltage is thus considerably reduced.

Fig. 6 shows an oscillogram of a highly displaced short circuit on a 26,700-kv-a. alternator. It may be seen that the initial instantaneous value of recovery voltage is reduced to less than 50 per cent.

E. *Effect of Initial Load Current*

The recovery voltage depends upon the current through the switch. This may include load current as well as fault current. The formulas given under part *C* may still be used in this case, if i is taken as the total reactive current through the switch.

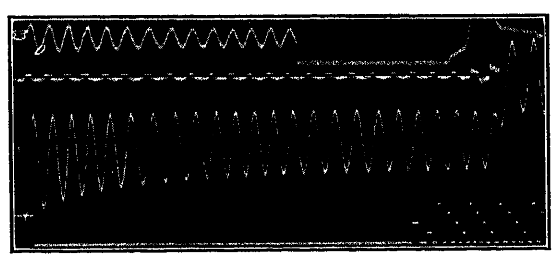

FIG. 5—OSCILLOGRAPHIC RECORD OF CURRENT AND VOLTAGE OF THE FIRST PHASE TO CLEAR OF A THREE-PHASE SHORT CIRCUIT AT 14,500 VOLTS ON THE SAME GENERATOR AS FIG. 4, BUT WITH AN AMORTISSEUR WINDING, OPERATING WITH THE NEUTRAL UNGROUNDED AND WITH NO EXTERNAL REACTANCE

F. *Effect of Saturation*

Saturation tends to reduce any overvoltage requiring an increase in the flux of the generator. If, therefore, the net effect of initial load current and the decrement factor tends to increase the recovery voltage, their effect will be modified by saturation.

The presence of flux at a density near saturation in the teeth and the end of the pole operates to cut down the permeability of these parts to a change in total flux in any direction. Quadrature axis flux has a greater length of path through the end of the pole than has

direct axis flux. Thus saturation probably tends to decrease the value of both quadrature reactance and the quadrature reactance factor.

The reduction in the quadrature reactance factor is apparently about 10 per cent for the 100,000-kv-a. testing generator in the plant of the company with which the authors have been associated.

High Frequency or "Rate of Rise" Phenomena

Qualitative Discussion of Important Types of Apparatus

Practically all of the high frequency phenomena attendant upon the build-up of recovery voltage are attributable to the capacitance to ground of apparatus between the circuit breaker terminals and the principal part or parts of the reactance limiting the short-circuit current.

There are six types of apparatus which are of importance from this point of view:

1. Transmission lines and cables.
2. High voltage bushings.
3. Station bus structure.
4. Transformers.
5. Current limiting reactors.
6. Rotating machines.

1. Transmission lines and cables are well known to be distributed circuits capable of supporting traveling waves. They act substantially as resistances until a wave has traveled from one end to the other and back, which, with a line of even moderate length, requires a time very much longer than is taken to reach crest voltage when no transmission lines are connected to the bus. The resistance corresponding to a transmission line is 300 or 400 ohms; that corresponding to a cable is 20 to 50 ohms.

2. High voltage bushings have a capacitance of 0.0001 to 0.0003 μf. They are of importance only when a number of them is connected to the circuit and there is very little capacitance of any other kind.

3. The capacitance of station bus structures varies widely according to voltage and kv-a. ratings. Its limits are probably about 0.001 μf and 0.02 μf. It is of importance only when no transmission line or cable is connected.

4. The effective capacitance to ground of the high voltage winding of a transformer varies from about 0.001 μf. to 0.002 μf., the higher values occurring with shielded transformers.

5. Current limiting reactors have a capacitance to ground of about 0.0001 μf., so that unless some apparatus of appreciable capacitance to ground is connected between the reactor and the circuit breaker, the frequency of recovery voltage may be as high as several hundred thousand cycles.

6. A rotating machine has a capacitance usually between one-tenth and one microfarad between the copper of its windings and the iron of its stator laminations. This capacitance determines the frequency and rate of rise of recovery voltage in the case of a dead short circuit on the machine.

Effect of Arc Voltage Just Previous to Interruption.

The form of the recovery voltage curve is usually an oscillation of one form or another starting from the value of arc voltage immediately before interruption, and having as its final center the voltage determined from low frequency considerations. In most of the calculations connected with this paper the arc voltage immediately before interruption is assumed zero. If this voltage is much different from zero, the initial amplitude of the oscillation is increased and the first peak of the high frequency oscillation is higher than otherwise. This effect is shown in the calculated curve of Fig. 12, in which the dotted line corresponds to the first half cycle at high frequency, as calculated on the basis of zero arc voltage immediately before interruption, and the full line corresponds to the curve actually obtained.

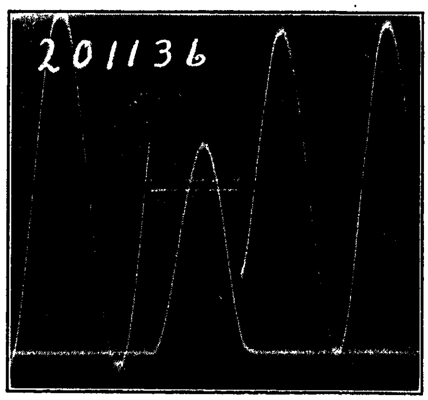

Fig. 6—Oscillographic Record of Current and Voltage for a Highly Displaced Short Circuit on a 26,700-Kv-A. Alternator

Recovery Voltage Rates on High-Voltage Systems

The extreme values of frequency and rate of rise of recovery voltage at the high side of a transformer are experienced when there is no apparatus of appreciable capacitance (say 0.0002 μf. or more) on either the high or low side of the transformer.

Under this condition, assuming an effective capacitance to ground of 0.001 μf. per transformer winding, the frequency and rate of rise are given by the equations.

$$f = \frac{3200}{\text{kv.}} \sqrt{\frac{\text{kv-a.}}{n\, k_q}} \text{ cycles per second}$$

and

$$r = 20\, k_a\, k_s \sqrt{\frac{\text{kv-a.} \times k_q}{n}} \text{ volts per microsecond.}$$

where

Kv-a. denotes the initial short circuit kv-a. per phase (neglecting the d-c. component of current),

Kv. denotes the leg voltage of the system before short circuit, in kilovolts,

and n denotes the number of transformers in parallel.

It should be appreciated that these formulas represent extreme conditions, and that even with only a moderate amount of bus structure and no transmission

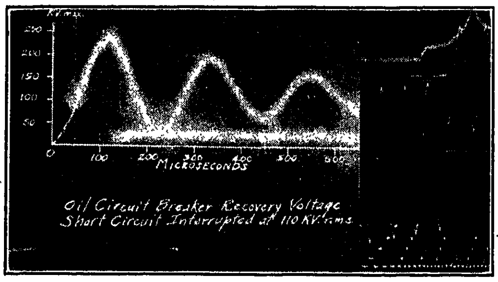

FIG. 7—CATHODE-RAY AND MAGNETIC OSCILLOGRAPHIC RECORDS OF THE RECOVERY VOLTAGE OF A 231,000 KV-A. SINGLE-PHASE SHORT CIRCUIT AT 110 KV., AT TRANSFORMER TERMINALS WITH NO TAP LINES

lines connected between circuit breaker and transformer, values lower than one-quarter of those given by the formulas may exist.

Fig. 7 shows cathode ray and magnetic oscillographic records of the recovery voltage following a single-phase 231,000-kv-a. short circuit (d-c. component neglected) for which $k_5 = 0.74$, on the 110-kv. connection of a cir-

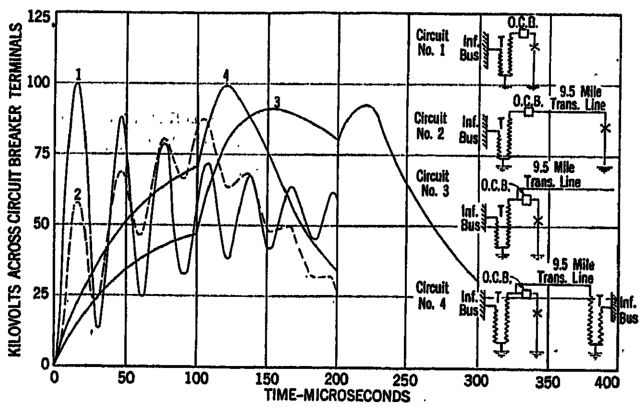

FIG. 8—CALCULATED RECOVERY VOLTAGE CURVES FOLLOWING A SINGLE-PHASE LINE-TO-GROUND SHORT-CIRCUIT AT POINTS MARKED X ON CIRCUIT DIAGRAMS

System voltage: 66,000
Capacity of transformer in each case: 20,000 kv-a. per phase
Transformer reactance: 10 per cent
Transmission line surge impedance: 400 ohms
Length of transmission line: 9.5 mi.

cuit breaker testing plant, two transformers being used in parallel. The frequency of the oscillation is 4,600 cycles per second, and the rate of recovery voltage rise about 2,400 volts per microsecond.

The values given by the formulas for extreme conditions are:

$$f = 9{,}800 \text{ cycles per second}$$

and $$r = 5{,}000 \text{ volts per microsecond.}$$

The discrepancy is ascribed to two factors:

1. Several hundred feet of line were required to parallel the transformers and connect to the circuit breaker.

2. Each transformer had six taps and therefore six bushings connected to the high side winding.

The beneficial effect of a capacitance to ground connected between the high side of a transformer and the circuit breaker is strikingly presented in Fig. 8, where calculated recovery voltages at the high side of a 20,000-kv-a., 38.1-kv. line-to-ground transformer following a single-phase line-to-ground short circuit are shown for the four circuits illustrated, the low-tension winding of the transformer being assumed connected to an infinite bus in each case.

It will be noted that the rates of rise of recovery voltage in curves Nos. 3 and 4 are very much less than those in curves Nos. 1 and 2. The change in the rate of rise of recovery voltage would be even more marked than is shown by Fig. 8 if—

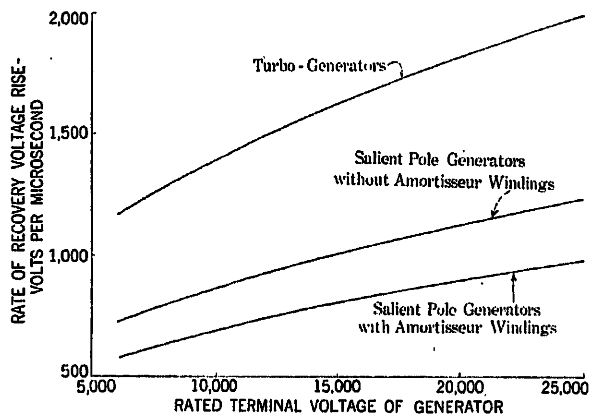

FIG. 9—RATES OF RECOVERY VOLTAGE RISE FOR THREE-PHASE UNGROUNDED SHORT CIRCUITS AT THE GENERATOR TERMINALS

1. The system voltage were higher.
2. The kv-a. capacity of the transformer were less.
3. More than one transmission line were connected between S_1 and T_1.

or

4. The transmission line L_2 were replaced by a cable.

It would be less marked if a bus of finite reactance were assumed on the low-tension side of the transformer.

The length of line L_2 has no effect on the rate of rise of recovery voltage except in changing the time when reflections return from the far end. The time when these reflections appear is approximately 10.6 microseconds per mile of line after the interruption. Thus with the 9.5-mile lines of Fig. 8, reflections return at $t = 100$ microseconds.

Recovery Voltage Rates on Low Voltage Systems

On the basis of average values for the design constants of a rotating machine, the rate of recovery voltage rise for the first phase to clear of an ungrounded

three-phase short circuit is given with reasonable accuracy by the curves of Fig. 9.

Figs. 10, 11, and 12 show cathode ray and magnetic oscillographic records of recovery voltages on the low-tension (14,500-volt) system of the circuit breaker testing plant of the company with which the authors have been associated, together with calculated curves. (Only the magnitudes and frequencies of the oscillations were calculated, the decrements being adjusted to correspond to the films.)

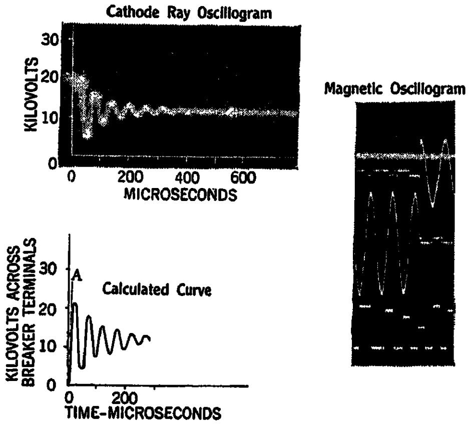

FIG. 10—CATHODE RAY- AND MAGNETIC OSCILLOGRAPHIC RECORDS AND CALCULATED CURVE FOR RECOVERY VOLTAGE OF THE FIRST PHASE TO CLEAR OF A THREE-PHASE GROUNDED SHORT CIRCUIT AT 14,500 VOLTS ON A SOLIDLY GROUNDED 100,000-KV-A. ALTERNATOR WITH THREE OHMS EXTERNAL REACTANCE IN SERIES PER PHASE

Fig. 10 shows a three-phase-to-ground short circuit on a solidly grounded generator with three ohms external reactance in series per phase.

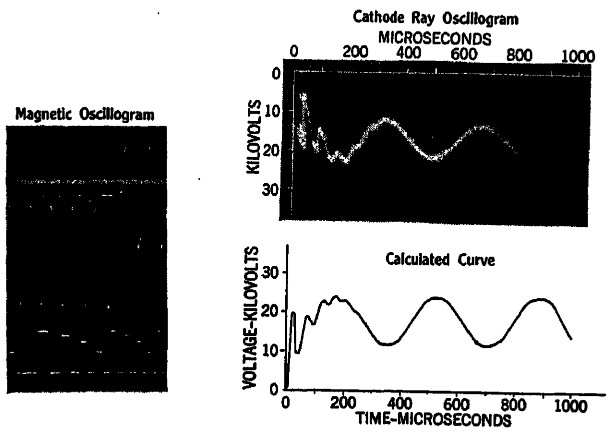

FIG. 11—CATHODE-RAY AND MAGNETIC OSCILLOGRAPHIC RECORDS AND CALCULATED CURVE FOR RECOVERY VOLTAGE OF THE FIRST PHASE TO CLEAR OF A THREE-PHASE GROUNDED SHORT CIRCUIT AT 14,500 VOLTS ON AN UNGROUNDED 100,000-KV-A. ALTERNATOR WITH THREE OHMS EXTERNAL REACTANCE IN SERIES PER PHASE

Fig. 11 shows the phenomena occurring on the first phase to clear of a three-phase-to-ground short circuit on an ungrounded generator with three ohms external reactance in series per phase.

Fig. 12 shows the recovery voltage of the first phase to clear of a two-phase-to-ground short circuit on an ungrounded generator with 6.1 ohms external reactance in each line. In the calculated curve of Fig. 12, the starting point was taken equal to the arc drop just prior to clearing, as shown on the magnetic oscillogram.

It will be noted that in both Fig. 11 and Fig. 12, oscillations occur at two widely different frequencies. This happens because the generator neutral is raised above ground potential during such a short circuit, and the two frequencies result (1) from oscillation of the bus capacitance to ground with the inductance in the line clearing first, and (2) from oscillation of the copper-to-iron capacitance of the generator with the inductance in the line remaining grounded. The two inductances having the same value and the capacitances having a ratio of approximately 100 to 1, the two frequencies have a ratio of approximately 10 to 1.

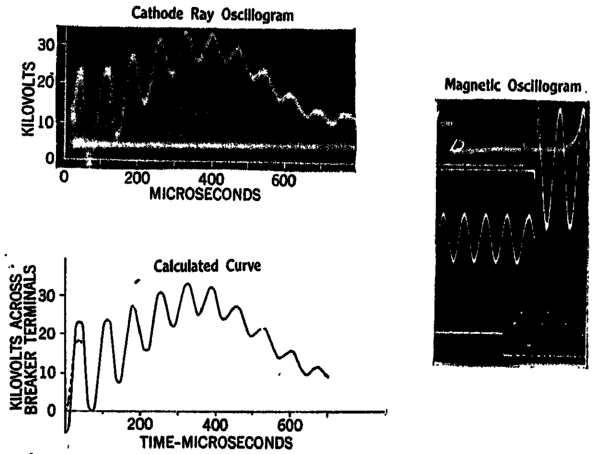

FIG. 12—MAGNETIC AND CATHODE-RAY OSCILLOGRAPHIC RECORDS AND CALCULATED CURVE OF THE RECOVERY VOLTAGE OF THE FIRST PHASE TO CLEAR OF A TWO-PHASE-TO-GROUND SHORT CIRCUIT AT 14,500 VOLTS ON AN UNGROUNDED 100,000-KV-A. GENERATOR WITH SIX OHMS EXTERNAL REACTANCE IN SERIES PER PHASE

It will be noted that in this case the maximum voltage is appreciably less than twice normal peak, due to the fact that the high frequency oscillation is almost completely damped out by the time the low frequency oscillation has reached its first peak. This may occur in any circuit in which the capacitance and reactance are so distributed as to give rise to oscillations of widely different frequencies and of about the same amplitude. Unless this is the case, however, or unless special damping is provided, an overshoot very nearly to twice normal, plus the negative arc voltage peak just prior to clearing, is almost sure to be experienced.

A comparison of the cathode ray and magnetic records of the recovery voltages in Figs. 7, 10, 11, and 12 shows very clearly that the magnetic record can not be relied upon to show correctly the high frequency components of the recovery voltage curve and that the circuits

having the highest recovery voltage rates may show the most innocent films, while circuits having a comparatively low rate of recovery voltage will show the oscillations correctly on the film, and thus give the impression of being very difficult to interrupt.

Effect of Parallel Resistance on the Rate of Rise of Recovery Voltage.

Resistance connected across the terminals of a circuit breaker tends to prevent overshooting and to cut down the rate of rise of recovery voltage. A resistance of 1,000 ohms so connected materially reduces the rate of rise of recovery voltage on a severe 220-kv.

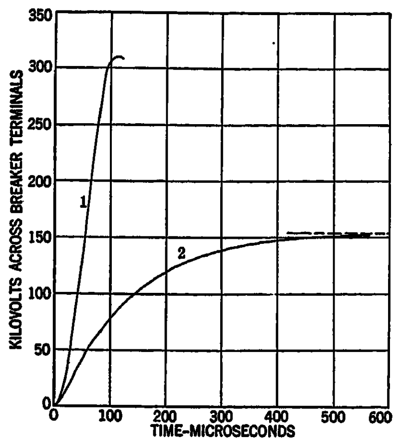

FIG. 13—RECOVERY VOLTAGE CURVES FOR TESTS ON EXPERIMENTAL EXPLOSION CHAMBER BREAKER

Curve No. 1 is for standard 110-kv. test circuit; Curve No. 2 is for standard 110-kv. test circuit modified by the connection of a 1,000-ohm resistor across the breaker terminals

short circuit, with no transmission lines connected between the breaker and the high side of the transformer.

On lower voltage systems a lower resistance is required for this purpose unless only a small amount of power is involved in the short circuit.

When one or more transmission lines are connected between the breaker and the high side of the transformer, the rate of rise of recovery voltage is already so low that a very low resistance is required to effect any further reduction.

Effect of Nature of Recovery Voltage on Breaker Operation

Mention was made in the introduction of two cases in which the nature of the recovery voltage curve had a very pronounced influence upon breaker operation. A few more details regarding these tests are given in this section, as well as brief reports of other data of this character.

As regards the tests on the Northern States Power Company system, power from the Riverside Station was supplied through step-up and step-down transformers with 43 miles of 110-kv. transmission line intervening. Thus stationary apparatus played a large part in the limitation of short-circuit current, and the quadrature reactance factor was low. Also, the circuit had sufficient capacitance to reduce its frequency to about 300 cycles. At Wissota, on the other hand, power was supplied directly from water-wheel generators, which have a high quadrature reactance factor (2.0 or greater), and the frequency of recovery voltage was probably about 5,000 or 6,000 cycles. The distress evidenced by the breakers was much greater at Wissota than at Riverside, as is shown by Table I.

In connection with the high voltage tests, apart from reflections, the resistance connected (about 1,000 ohms) had approximately the correct value to duplicate the effect of a single transmission line connected as in diagrams Nos. 3 and 4 of Fig. 8 upon the recovery voltage of a single-phase short circuit of three times the kv-a. available in the test, or approximately 600,000 kv-a., single-phase.

On the standard test circuit, the breaker cleared on the 66-kv. connection, requiring from 58 to 73 per cent of its total contact separation, and failed to clear on the 88-kv. and 110-kv. connections. With the resistance connected across the breaker terminals, the breaker cleared consistently, not only on the 88-kv. and 110-kv. connections, but also on the 132-kv. connection, the maximum arc length being only 58 per cent of the total stroke.

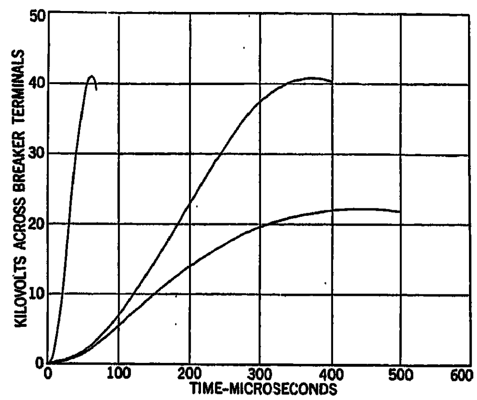

FIG. 14—CALCULATED RECOVERY VOLTAGE CURVES FOR TESTS ON 15,000-VOLT BREAKER

Recovery voltage curves for the two conditions are shown in Fig. 13, that for the standard circuit being taken from the cathode ray oscillogram of Fig. 7, and the modification due to the connection of the resistor being calculated.

A decrement factor of 1.0 is assumed for both curves.

A short series of tests has been made under the direction of the authors of this paper upon a plain-break oil circuit breaker at 14,500 volts and from 800 to 1,200 amperes. The circuit had an oscillating frequency of about 8,000 cycles for the first group of tests. For the second group of tests the oscillating frequency was reduced to 1,300 cycles by the addition of a shunt capacitor, while for the third group, the 1,300-cycle circuit was very nearly critically damped by resistance connected across the breaker terminals. Calculated recovery voltage curves for the three groups of tests are shown in Fig. 14. It was found that the arc length

in the second group of tests was approximately 10 per cent shorter than in the first group, while in the third group, the reduction was 30 per cent.

Biermanns has reported a series of tests on a plain-break breaker at 7,500 volts and about 20,000 amperes at recovery voltage frequencies of 100,000 cycles, 1,300 cycles, and 500 cycles. At 1,300 cycles, he finds the arc lengths only about five per cent less than at 100,000 cycles, but at 500 cycles, the arc length is reduced to 50 per cent of its value at 1,300 cycles. This would indicate that the operation of this type of breaker is independent of recovery voltage frequency when this frequency is above about 1,000 cycles, but is improved

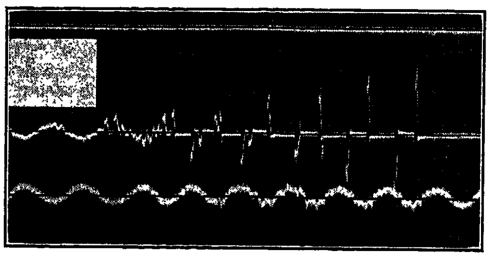

FIG. 15—OSCILLOGRAPHIC RECORD OF THE OPENING OF A 220-KV. TRANSMISSION LINE CHARGING CURRENT

considerably by any appreciable reduction of this frequency below that value.

It will be noted, as a matter of interest, that the results obtained on the Northern States Power Company tests are consistent with this deduction.

Interruption of Line Charging Currents

It has long been known that the interruption of transmission line or cable charging currents may be accompanied by severe overvoltages. Fig. 15 shows a magnetic oscillogram of the current obtained on such a test on a 220-kv. transmission line. Analysis indicates that the voltage appearing across the switch just previous to a current surge should be roughly equal to the product of line surge impedance and the peak current in the surge. On this basis, this oscillogram indicates a voltage equal to several times normal peak. The fact that such voltage actually occurs is borne out by surge recorder data.

This phenomenon occurs as follows. The arc is extinguished at the time when the current is zero and the transmission line completely charged to one polarity. One half-cycle later the transformer terminal voltage has reversed its polarity, but the voltage of the transmission line has remained unchanged. Double leg voltage, therefore, exists across the switch. This voltage may be sufficient to break down the gap, or the gap may be broken down while this voltage is building up. If this occurs, the gap conducts current while a wave travels down the line, is reflected at the end, and travels back, reversing the potential of the line with respect to the transformer and charging the line up to a potential which may be as high as three times normal. When this has occurred, the current in the breaker drops to zero, so that the arc is again interrupted. The transformer side of the breaker then changes polarity during the next half-cycle, while the transmission line holds its charge and potential. This time the voltage across the gap may reach four times normal peak, and thus the gap may again be broken down. The oscillation is then repeated, again reversing the polarity of the line and leaving it at a potential which may be as high as five times normal. On a long transmission line with no leakage, there is no theoretical limit to the voltage which may build up in this manner, and voltages as high as 5.5 times normal have been recorded on transmission lines in operation. The principal agent in setting this limit is probably corona loss.

This phenomenon should be expected to be more common on high voltage circuits than on low-voltage circuits, for if the circuit breaker increases its dielectric strength at the rate of twice normal crest voltage per half cycle, the phenomenon will not occur.

The phenomenon can be eliminated by putting a high resistance leak on the line to draw off its charge or by using a breaker designed to increase its dielectric strength at a sufficient rate.

Part II

THEORY AND CALCULATIONS

In this part, as in Part I, the low frequency and high frequency phenomena are considered separately, the low frequency phenomena first, and the high frequency phenomena afterward.

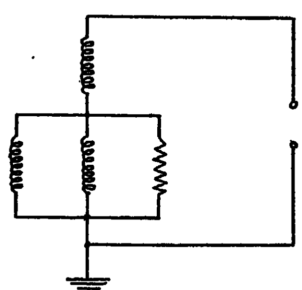

FIG. 16—CIRCUIT FOR THE FIRST PHASE TO CLEAR OF A THREE-PHASE GROUNDED SHORT CIRCUIT ON A GENERATOR WITH THE NEUTRAL GROUNDED THROUGH A RESISTANCE

In both cases, the calculations are made by means of the principle of superposition. This principle is stated as follows: In any network unappreciably affected by saturation and hysteresis, if the mechanical displacements of moving parts during the period under consideration are unaffected by the disturbance, the changes in voltages and currents throughout the network due to a change in voltage, Δe, or current, Δi, applied at any point are equal, at any instant, to the voltages and currents flowing as a result of the application at that point of a voltage, Δe, or current, Δi, when no other voltage or current is applied to the network. This is true of both transient and sustained

conditions. Using this principle to determine the voltage arising across a circuit breaker upon the final interruption of current, we have, just before the interruption.

$$i_1 = I_0 [\sin (w t + \phi) - \sin \phi] \quad (1)$$

and $e_1 = 0$ (2)

After the interruption, $i_2 = 0$ (3)

hence, for the change in current, we have

$$\Delta i = i_2 - i_1 = 0 - I_0 [\sin (w t + \phi) - \sin \phi] \quad (4)$$

The change in voltage at the time of interruption, Δe, and the voltage, e_2, appearing after the interruption, are, therefore, given by

$$e_2 = 0 + \Delta e = 0 - I_0 [\sin (w t + \phi) - \sin \phi] Z \quad (5)$$

where Z is an operator representing the effective impedance of the network at the point of interruption.

In a simple series circuit containing only resistance and reactance, or if the circuit has parallel branches all of which have substantially the same phase angle, Z may be calculated as a complex quantity. In applying this complex quantity to Equation (**5**), the real component should be applied to both d-c. and a-c. components of current, but the imaginary component should be applied only to the a-c. component of current and should involve a forward phase shift of 90 deg. Thus, for example, if, when the values of the variables are substituted, Equation (**5**) becomes

$$\Delta e = - 10 [\sin (w t + 30^0) - \sin 30^0] (1 + j 5) \quad (5a)$$

by using the correct application of the operator $(1 + j 5)$, we obtain

$$\Delta e = -10 [\sin(w t+30^0) - \sin 30^0] - 50 \cos (w t+30^0) \quad (5b)$$

In a circuit having parallel branches of different phase angle, the voltage rapidly attained may be determined by considering all resistances as short circuits. The peak value of voltage is very nearly that given by Equation (**5**). The curve joining the two is a combination of logarithmics, one for each parallel circuit. The time constants of these logarithmics depend upon the relative values of resistance and inductance in the circuits to which they apply.

Low Frequency Phenomena

Effect of Type of Short Circuit and Circuit Conditions

For a given value of I_0, then, the recovery voltage depends upon the value of ϕ and the nature and magnitude of Z; ϕ depends purely upon the displacement of the current wave, and its effect can be more conveniently discussed after the effect of circuit conditions.

a. Resistance vs. Reactance. It has long been known that a current flowing in a resistive circuit is much easier to interrupt than the same current flowing in a reactive circuit, with the same r. m. s. value of re-established voltage. This is to be expected from the fact that a negative sine wave of current impressed upon a resistive circuit gives rise to a voltage wave across the terminals of the circuit which is in phase with the current and therefore starts at zero; whereas a negative sine wave of current impressed upon a reactive circuit gives rise to a voltage wave which is 90 deg. out of phase with the current and therefore, neglecting high frequency transients, starts at its crest value.

This may also be seen from Equations (**5**), (**5a**), and (**5b**) in that the real part of the operator Z, which arises from the resistance of the circuit, gives rise to sine terms in the recovery voltage, whereas the imaginary part, which arises from the reactance of the circuit, gives rise to cosine terms in the recovery voltage.

Of two short-circuit currents having the same magnitude and phase angle and the same system voltage, but in one of which the current is limited by a resistance and reactance in series, and in the other by resistance and reactance in parallel, the parallel circuit is the easier to clear, for in the series circuit, the voltage rises at a high rate to a value $L \dfrac{d i}{d t}$, whereas in the parallel circuit the voltage rises from the start along a comparatively slow exponential curve.

b. Type of Short Circuit. The effective impedance of the network to the point of short circuit depends upon the constants of the network and also upon the type of short circuit that is interrupted.

Where the effects of stationary apparatus predominate over those of rotating machinery, for single-phase short circuits, either line-to-ground or line-to-line, the effective impedance of the network is the same as the impedance limiting the short-circuit current:

$\dfrac{Z_0 + Z_1 + Z_2}{3}$ for line-to-ground short circuits and

$Z_1 + Z_2$ for line-to-line short circuits.

Thus the voltage after interruption will be the same, except for high frequency effects, as the voltage before establishment of the short circuit. This is confirmed by the oscillogram of Fig. 1, shown in Part I.

In the case of two-phase-to-ground short circuits on a grounded system and three-phase short circuits on a grounded or ungrounded system, however, one phase always clears ahead of the others, and the effective impedance which the network offers to the breaker in the phase clearing first may be different from that which limits the short-circuit current.

These impedances are calculated by the method of symmetrical phase-sequence components in Appendix A. For the case of the first phase to clear of a three-phase short circuit the impedance is given by

$$Z = \frac{3 Z_0 Z_1 Z_2}{Z_0 Z_2 + Z_1 Z_0 + Z_1 Z_2} \quad (6)$$

This solution is, of course, for a grounded neutral system and the effect of neutral impedance may be taken into account in the value assigned to Z_0.

It should be noted at this point that a difference in the recovery voltage characteristic of a three-phase grounded short circuit arises depending on whether

the neutral impedance is a resistor or a reactor. If it is a reactor, the voltage rises immediately to $i\,Z$, where Z has the value given by Equation (**6**). If the neutral impedance is a resistor, however, the circuit is that of Fig. 16, where x_a is the reactance to neutral offered to the phase clearing first and x_b and x_c together represent the reactance of the other two phases. The voltage rapidly attained is that calculated by considering the resistance as a short circuit:

$$e = i\,\frac{3\,X_0\,X_1\,X_2}{X_0\,X_2 + X_1\,X_0 + X_1\,X_2} \qquad (\mathbf{6a})$$

The peak value is that indicated by Equation (**6**). The curve joining the two is a logarithmic whose time constant is that given by the neutral resistor in series with the reactances x_b and x_c in parallel. This time constant is, in electrical radians

$$t_0 = \frac{X_1\,X_2 + X_2\,X_0 + X_0\,X_1}{2\,R\,(X_1 + X_2)} \qquad (\mathbf{6b})$$

where R is the neutral resistance.

The relative values $X_1 = X_2 = 2\,X_0 = \dfrac{R}{4}$ are such as to give a time constant somewhat longer than average, but by no means unusual. Substituting these values,

$$t_0 = 0.125 \text{ rad} = 7.2^0$$

In an ungrounded system, or in a grounded system when the ground is not involved in the short circuit, Z_0 is equal to infinity and equation (**6**) becomes

$$Z = \frac{3\,Z_1\,Z_2}{Z_1 + Z_2} \qquad (\mathbf{7})$$

and if $Z_1 = Z_2$, as is the case except in rotating machinery, equation (**7**) may be still further simplified:

$$Z = \frac{3}{2}\,Z_1 \qquad (\mathbf{8})$$

If the impedance of stationary apparatus predominates, the current in a three-phase short circuit is given by

$$I = \frac{E}{Z_1} \qquad (\mathbf{9})$$

where E is the normal system voltage to ground. Multiplying equations (**8**) and (**9**) we have

$$e = Z\,I = \frac{3\,E}{2} \qquad (\mathbf{10})$$

showing that the recovery voltage of the first phase to clear of a three-phase short circuit, where the impedance of stationary apparatus predominates, neglecting high frequency effects, is 1.5 times the Y-phase voltage existing before short circuit. This effect is shown in Fig. 2, Part I.

The impedance encountered by the first phase to clear of a two-phase-to-ground short circuit is also calculated in Appendix A. It is there shown to be,

$$Z = \frac{e}{i} = \frac{Z_0\,Z_1 + Z_0\,Z_2 + Z_1\,Z_2}{Z_1 + Z_2 + Z_0} \qquad (\mathbf{11})$$

Effect of Rotating Machinery

It is a familiar fact that in any fault at all close to a generator, the current is subject to considerable variation; decaying considerably from its initial value on machines subject to hand regulation; and starting to decay, but being brought finally to a value not greatly different from the initial value, in machines whose excitation is controlled by a quick response excitation system. The negative current at the time of interruption being equal and opposite to this short-circuit current, and the reactance encountered by this negative current being a constant, it follows that the recovery voltage is decreased in magnitude exactly in proportion with the a-c. component of current.

This same conclusion may be reached from another point of view, for the decay in short-circuit current is but a manifestation of decay in rotor flux, and a decay in rotor flux must also cause a proportionate decay in open-circuit voltage.

In Part I, the factor by which the recovery voltage is altered by this decay in flux is called the decrement factor and is designated by the symbol k_δ.

In Appendixes B, C, and D, there is a rather involved mathematical discussion, in which the phenomena accompanying the flow and interruption of short-circuit current in rotating machinery are treated in some detail by the method first used by Messrs. Doherty and Nickle in their papers on synchronous machines. A brief discussion is offered at this point, however, in which an effort is made to base the argument on physical conceptions rather than on mathematics. The same results are obtained in the two cases.

In the case of a single-phase short circuit, either line-to-ground or line-to-line, the reactance determining the recovery voltage is the same as that initially limiting the short-circuit current. The recovery voltage, therefore, is equal to the decrement factor times the voltage before short circuit. There is very little distortion in the recovery voltage wave, even though the short-circuit current wave is considerably distorted.

These facts are well brought out in Fig. 17 which shows an oscillogram of a dead short circuit, single-phase, at 14,500-volts on a 100,000-kv-a. alternator without an amortisseur winding.

On this test,

The r. m. s. voltage before short circuit, as measured by a voltmeter is......................	14,500 volts
The decrement factor, as determined from the short-circuit current curve is.................	0.74
The calculated peak value of recovery voltage is, therefore, 14,500 × $\sqrt{2}$ × 0.74 or............	15,200 volts
The value of crest voltage measured on the film is..	15.900 volts

In a purely reactive three-phase short circuit, after the displacement has disappeared, when the current in any phase passes through zero, that phase is linking the quadrature axis of the alternator. The reactance which a negative current will encounter upon entering the machine at that instant, therefore, is the quadrature subtransient reactance of the machine.

Unless both short circuit and alternator are solidly grounded, the current of the first phase to clear passes through its own phase winding and also through those

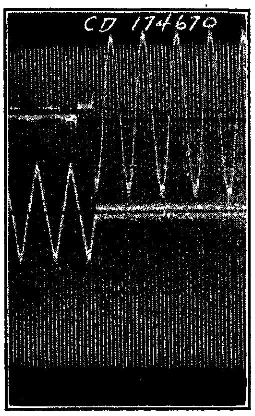

FIG. 17—OSCILLOGRAPHIC RECORD OF CURRENT AND VOLTAGE OF A SINGLE-PHASE LINE-TO-LINE SHORT CIRCUIT AT 14,500 VOLTS ON A 100,000-KV-A. SALIENT-POLE GENERATOR WITHOUT AN AMORTISSEUR WINDING WITH ZERO EXTERNAL REACTANCE

of the other two phases in parallel. The reactance is thus—

$$z = \frac{3}{2}\, x_q'' \tag{12}$$

and the voltage at the instant of clearing is

$$e_m = \frac{3}{2}\, i_m\, x_q'' \tag{13}$$

where i_m is the crest value of current flowing just before short circuit. The case of a grounded short circuit is solved in Appendix C. The solution is given by Equation (14:)

$$z = \frac{3\, x_q''\, z_0}{x_q'' + 2\, z_0} \tag{14}$$

where z_0 is the zero-phase-sequence impedance at the point of short circuit. The remarks with regard to the comparative effect of resistance and reactance in the neutral also apply here.

The impedance representing the first phase to clear in a two-phase-to-ground short circuit is somewhat more difficult to visualize. The following equations are taken from the analysis in Appendix D and apply only for purely reactive circuits:

$$z = \frac{2\,(x_d''x_q'' + x_q''x_0 + x_0 x_d'')\,(x_q''^2 + x_q''x_0 + x_0^2) + x_0(x_q'' - x_d'')\,(-\,x_q''^2 + 2\,x_q''x_0 + 2\,x_0^2)}{x_d''\,(2\,x_q'' + x_0)^2 + x_0\,(2\,x_q'' + x_0)\,(x_q'' + 2\,x_0)} \tag{15}$$

$$e = E\,\frac{2\sqrt{3}\,(x_q''^2 + x_q''\,x_0 + x_0^2)^{3/2}}{x_d''(2\,x_q'' + x_0)^2 + x_0(2\,x_q'' + x_0)(x_q'' + 2\,x_0)} \tag{16}$$

It may be inferred from the fact that the instantaneous position of the generator winding with respect to the rotor is the principal factor governing the impedance encountered by the negative current that, with the change in the position of the winding with respect to the rotor which occurs throughout the cycle, the impedance of the winding will change so that a sine wave of negative current will give rise to a distorted voltage wave. That this is the case for other than single-phase short circuits is brought out quite clearly from the theoretical viewpoint in Appendix B and verified by the oscillograms of Figs. 4 and 18 for the three-phase case. In the case of single-phase short circuits, however, the distortion occurs in the current wave and the recovery voltage has the characteristic open circuit wave form of the machine, as shown in Fig. 17. In the case of a two-phase-to-ground short circuit on a grounded system, the wave forms of both the current and the recovery voltage of the first phase to clear are likely to be distorted.

On account of this distortion, initial values of voltage are considered instead of r. m. s. values.

Of all these cases, the two giving the highest value of voltage across the circuit breaker terminals are the first phase to open of a three-phase short circuit in which either short circuit or generator is ungrounded, as given by Equation (13), and the first phase to clear of a two-phase-to-ground short circuit with high neutral impedance. In the first case, the current i is limited only

FIG. 18—OSCILLOGRAPHIC RECORD OF THE RECOVERY VOLTAGE OF THE FIRST PHASE TO CLEAR OF A THREE-PHASE UNGROUNDED SHORT CIRCUIT AT 14,500 VOLTS ON A 100,000-KV-A. ALTERNATOR WITHOUT AN AMORTISSEUR WINDING AND WITH ZERO EXTERNAL REACTANCE

by x_d'' and decrement, so that for a three-phase ungrounded short circuit interrupted well up on the decrement curve,

$$i_m = \frac{E_m}{x_d''} \tag{17}$$

and

$$e_m = \frac{3}{2}\, E_m\, \frac{x_q''}{x_d''} \tag{18}$$

where E_m is the crest value of normal phase-to-neutral voltage.

In the general case, in which several machines feed the short circuit through various stationary reactances, x_q'' and x_d'' must be replaced by s_q'' and s_d'', which are the reactances of the system to the point of short circuit, using x_q'' for the reactance of all machines in determining s_q'', and x_d'' for the reactance of all machines in determining s_d''.

The ratio $\frac{s_q''}{s_d''}$ is, in general, less than the value of $\frac{x_q''}{x_d''}$ for the average machine of the system, so reactance external to the machines mitigates the effect of unequal reactances in the two axes. In Part I the ratio $\frac{s_q''}{s_d''}$ has been called k_q.

In the case of a two-phase-to-ground short circuit on a system whose neutral is grounded through a high impedance, the current is substantially that of a line-to-line short circuit, and the reactance encountered by the negative current at the time of clearing substantially that determining the short-circuit current; so that the recovery voltage is the full line-to-line voltage of the system (if the decrement factor is unity). Since at the time the first phase clears, the other pole of the breaker may continue to carry sufficient current for a fraction of a cycle to render it conducting, all of this voltage appears across a single pole of the breaker. This voltage may approach very closely

$$e_m = \sqrt{3}\, E_m \tag{19}$$

In addition to the effect mentioned in connection with stationary apparatus, series resistance shifts the position of the winding with respect to the rotor axes at the time when its current ceases, and thus makes its reactance more nearly that corresponding to the direct axis.

In laminated rotor machines without amortisseur windings, the ratio $\frac{x_q''}{x_d''}$ is comparatively high, averaging about 2.0 or 2.5. This is because the field winding practically prevents, for the duration of a rapidly interrupted short circuit, any change in the value of rotor flux in the direct axis, thus limiting the value of x_d'' to slot and end turn reactance, whereas there is nothing except the air gap, and the metal rotor wedges of a round rotor machine, to limit the building up of flux in the quadrature axis.

Any conducting path which limits the amount of flux which can be built up, in a thousandth of a second or so, in the quadrature axis of a machine limits x_q'' in proportion. Thus an amortisseur winding reduces both x_d'' and x_q'', but the reduction in x_q'' is so much greater that the two become very nearly equal. The iron of a solid round rotor machine serves much the same purpose as the amortisseur winding of a salient-pole machine, and the ratio $\frac{x_q''}{x_d''}$ for solid rotor machines is only about 1.45.

The effect of an amortisseur winding is well brought out by the oscillograms of Figs. 4, 5, 18, and 19. All these oscillograms show the voltage across the first phase to clear of a three-phase grounded short circuit on an ungrounded machine, the generator used being the 100,000-kv-a. alternator used by the company with which the authors have been associated in its circuit breaker testing plant. The oscillograms of Figs. 4 and 18, however, were taken before, and the oscillograms of Figs. 5 and 19 after, the amortisseur winding was installed on that machine. Figs. 4 and 5 are taken with a comparatively slow film speed so that the entire short circuit could be recorded on a reasonably short film, while for Figs. 18 and 19, the film was run at a high speed so that the wave form could be observed. It will be noted that the overvoltage shown in Fig. 4 is much greater than that shown in Fig. 5 and that Fig. 18 shows a prominent third harmonic up until the time when the two later phases clear, which hardly appears at all in Fig. 19. Both Figs. 18 and 19 show a rather fuzzy curve up to the time when the two later phases clear, and in Fig. 5 this fuzziness shows up even on the slow film.

The difference in overvoltage between Fig. 4 and Fig. 5 checks with what is to be expected from the quadrature reactance factors for the two cases, as shown by the calculations below:

Quantities	Fig. 4	Fig. 5
Amortisseur winding	No	Yes
Decrement factor	0.63	0.50
Factor for three-phase short circuit on an ungrounded machine	1.50	1.50
Line-to-line voltage before short circuit (measured by voltmeter)	13,200	14,500
Peak value of recovery voltage	16,200	11,400
Quadrature reactance factor as calculated from above quantities:		
(a) $\dfrac{16{,}200}{\frac{13{,}200}{\sqrt{3}} \times \sqrt{2} \times 1.5 \times .63}$	1.58	..
(b) $\dfrac{11{,}400}{\frac{14{,}500}{\sqrt{3}} \times \sqrt{2} \times 1.5 \times 0.50}$	..	1.28
Quadrature reactance factor as determined from static tests—		
a. At zero field	1.73	1.38
b. At full field	..	1.28

As has been previously brought out, the distortion is to be expected with a high quadrature reactance factor.

The fuzziness or irregularity of the voltage wave is due to the inequality of the arc voltage on the two phases still carrying current, for the potential of the entire generator with respect to ground has a term equal

to one-half the difference of these two arc voltages. The departure of the actual voltage wave from its calculated value on account of this effect is limited to one-half the arc voltage of one of these other phases.

An induction motor is a laminated rotor machine with an amortisseur, whether it be a squirrel cage or polyphase wound rotor machine. Here the ratio $\frac{x_q''}{x_d''}$ is unity, due to the exact similarity of the two axes; for in an induction motor, the direct axis is distinguished from the quadrature axis only by the fact that for the moment it happens to be the axis of the rotor flux. The rotor flux of an induction motor is subject to about the same decrement as the d-c. component of a synchronous motor short circuit, so that short-circuit currents from induction motors are of no importance in a short circuit lasting more than four or five cycles, but a large induction motor connected to a short-circuited bus offers a

FIG. 19—OSCILLOGRAPHIC RECORD OF THE RECOVERY VOLTAGE OF THE FIRST PHASE TO CLEAR OF A THREE-PHASE SHORT CIRCUIT AT 14,500 VOLTS ON SAME GENERATOR AS FIG. 18, BUT AFTER THE AMORTISSEUR WINDING WAS INSTALLED

low reactance for the negative current that flows when the short circuit is cleared, and thus makes the circuit easy to interrupt.

Table III, Part I, gives the values of $\frac{x_q''}{x_d''}$ which may be expected for various types of machines.

Effect of Displacement

Displacement has the effect of shifting, with respect to the a-c. component, the time at which a short-circuit current wave passes through zero; hence it decreases the rate of change of current at that time and the initial instantaneous value of recovery voltage. In the case of rotating machines with unequal reactances in the direct and quadrature axes, displacement will have the additional effect of shifting the position of the winding at the time of current zero from directly in line with the quadrature axis of the rotor, to a position more nearly in line with the direct axis; thus it reduces the reactance of the circuit at the instant of clearing.

An oscillogram of a highly displaced short circuit is shown in Fig. 6, Part I.

HIGH FREQUENCY PHENOMENA

The high frequency phenomena accompanying the interruption of a short circuit are primarily attributable to the capacitances and leakage resistances existing at various points of the circuit—particularly, close to the circuit breaker. They may be calculated by setting up the circuit with the proper reactances and assigning the proper capacitance or resistance at each point, and solving.

A discussion of the types of apparatus important from the point of view of high frequency phenomena is given in Part I. A few details, however, which were omitted there, are conveniently mentioned at this point.

Transmission lines and cables are well and widely known to be distributed circuits capable of supporting traveling surges. In such a surge, a current of any given magnitude is always associated with a proportionate voltage, so that, from the point at which a surge is impressed, until reflections appear, the circuit appears to be a resistance. The ratio of voltage to current in such a surge is known as the surge impedance of the line. In overhead transmission lines the surge impedance is usually about 300 or 400 ohms; in cables it is much lower, varying from 20 to 50 ohms. The rate of propagation of waves on transmission lines is very close to the speed of light, about 1,000 ft. per microsecond. In cables the speed of propagation is only about 300 to 500 ft. per microsecond.

At an open end of a transmission line or cable a wave is reflected with reversed current and voltage of the same polarity. At a short-circuited end, the reflected voltage is reversed and the current has the same polarity as that of the approaching wave. Partial reflections occur at any discontinuities.

The minimum possible effective value of capacitance between the circuit breaker and transformer is the effective capacitance of the transformer winding plus the capacitance of one circuit-breaker bushing and one transformer bushing. This capacitance may be as low as 0.001 microfarad per transformer.

The inductance of the circuit is determined from the short-circuit kv-a.: If "kv." represents the transformer leg voltage before short-circuit in kilovolts, and "kv-a." the initial short-circuit kv-a. per phase for a fault right at the terminal of the transformer, at 60 cycles,

$$L = \frac{1000}{2\,\pi f}\,\frac{(\text{kv.})^2}{\text{kv-a.}}\,k_q = 2.65\,\frac{(\text{kv.})^2}{\text{kv-a.}}\,k_q \text{ henrys per phase (at sixty cycles)} \quad (20)$$

On the basis of this value of inductance and a capacitance of 0.001 μf. (10^{-9} farad) per transformer, the extreme frequency of the recovery voltage is given by

$$f = \frac{1}{2\,\pi\sqrt{L\,C}} = \frac{10^4}{2\,\pi\sqrt{0.26\dfrac{(\text{kv.})\,n\,k_q}{\text{kv-a.}}}}$$

$$= \frac{3200}{\text{kv.}}\sqrt{\frac{\text{kv-a.}}{n\,k_q}} \text{ cycles} \quad (21)$$

and the maximum rate of recovery voltage

$$r = 20\, k_\delta \sqrt{k_q\, k_v\, \text{kv-a.}/n} \text{ volts per microsecond} \tag{22}$$

in which

kv. = leg voltage of the transformer.
kv-a. = kv-a. per phase of the short circuit.
and

n = the number of transformers feeding the short circuit.

For a 200,000-kv-a. single-phase line-to-ground short circuit on one transformer at 38.1 kv. (66-kv. line-to-line) these values are f = 38,000 cycles and r = 10,500 volts per microsecond. It should be noted that these conditions are extreme and that under actual operating conditions the capacitance of bus structure and all transformers over one connected to the bus may be sufficient to cut both frequency and rate of recovery voltage to less than one-quarter of these values.

A rotating machine appears, from a theoretical standpoint, very similar to a transmission line, and it has been shown to react to lightning surges in much the same manner as a transmission line, even to the extent that oscillations due to reflection disappear when the correct value of resistance is connected to the machine neutral.

For the type of surge resulting from a circuit breaker interruption, however, the voltage at the terminals of the machine loses the straight lines and sharp corners that would be expected on a transmission line on account of the capacitance of buses, bushings, etc., connected at its terminals and on account of reflections at discontinuities within the winding. The oscillations in recovery voltage are, therefore, very nearly sinusoidal in shape, as would be the case in a lumped circuit. Their frequency, however, is equal to $\dfrac{1}{4\sqrt{L\,C}}$ as for a transmission line instead of $\dfrac{1}{2\,\pi\sqrt{L\,C}}$ as for a lumped circuit, L and C representing quadrature inductance per Y-phase and capacitance per Y-phase.

Approximate values of L, C, frequency, and rate of recovery voltage rise for the first phase to clear of a three-phase ungrounded short circuit are given in Equations (23), (24), (25), and (26), below, the values for the constants of these equations being given in Table IV. Fig. 9, Part I, shows a graph of Equation (26), giving the rate of recovery voltage rise for the first phase to clear of a three-phase ungrounded short circuit at the generator terminals.

It must be appreciated, of course, that such equations and curves as these require the assumption of specific values for many of the design constants of the machines, and that variations from assumed values in individual machines will cause variations from the values of L, C, f, and r given by these equations and curves. The one of these constants whose variation most affects these quantities appears to be the peripheral velocity. This has been assumed as 11,000 ft/min. in salient-pole machines with amortisseurs, 10,000 ft/min. in salient-pole machines without amortisseurs, and 22,000 ft/min. in turbo-alternators. The values actually used in water-wheel generators vary all the way from 5,000 ft/min. to 18,000 ft/min., the lower values occurring with low-head low-power installations, and the higher values with high-head high-power installations. Values of L and C are roughly inversely proportional to peripheral velocity, and values of f and r, directly proportional to peripheral velocity.

$$C = k_c \frac{M\,V\,A}{\sqrt{\text{kv.}}\ (1 + 0.08\ \text{kv.})} \text{ microfarads per phase} \tag{23}$$

$$L = k_L \frac{(\text{kv.})^2}{M\,V\,A} \text{ henrys per } Y\text{-phase} \tag{24}$$

$$f = k_f \frac{\sqrt[4]{\text{kv.}\ (1 + 0.08\ \text{kv.})}}{\text{kv.}} \text{ cycles per second} \tag{25}$$

$$r = k_r \sqrt[4]{\text{kv.}\ (1 + 0.08\ \text{kv.})} \text{ volts per microsecond} \tag{26}$$

TABLE IV
VALUES OF CONSTANTS

	k_C	k_L	k_f	k_r
Solid round rotors	0.0187	0.00048	83,500	679
Salient-pole generators without amortisseurs	0.0347	0.00172	32,300	420
Salient-pole generators with amortisseurs	0.0317	0.00061	57,100	334

If the neutral of a rotating machine is grounded through resistance, and if the short circuit is grounded, the neutral resistance is in parallel with the inductance of the last two phases to clear of a three-phase-to-ground short circuit. If the value of resistance is comparable with or less than the value of $\dfrac{1}{2}\sqrt{\dfrac{L}{C}}$ for these last phases it will damp out the oscillations of voltage across these phases rapidly enough to reduce appreciably the peak value of the second half-cycle, and to delay this peak several hundred microseconds.

Solution of Simple Circuits

Solutions are briefly presented here for five simple circuits as follows:

1. A three-phase-to-ground short circuit on a solidly grounded generator with three ohms external reactance in series per phase.
2. First phase to clear of a three-phase-to-ground short circuit on an ungrounded generator with three ohms external reactance in series per phase.
3. The first phase to clear of a three-phase ungrounded short circuit at the generator terminals.
4. Single-phase-to-ground short circuit approximately 10 miles out on a transmission line; circuit breaker directly connected to the high side of the transformer; transformer neutral solidly grounded; low-voltage side of transformer connected to an infinite bus.

5. Single-phase to ground short circuit on transmission line side of circuit breaker; a second transmission line approximately 10 miles long is connected between the circuit breaker and the transformer and is open circuited at the far end; transformer neutral is solidly grounded; low side of transformer is connected to an infinite bus.

1. The recovery voltage following a three-phase grounded short circuit on a solidly grounded generator with three ohms reactance in series per phase.

Generator voltage = 14,500 volts line to line, 8400 volts line to neutral.

Generator reactances: $x_q'' = 0.77$ ohm; $x_d'' = 0.60$ ohm; $x_0 = 0.05$ ohm.

The external reactance in this case is high enough so that $k_\delta = 1.0$.

Bus capacitance to ground = 0.008 μf per phase.

$$k_g = \frac{3 \times 3.05}{3.77 + 2 \times 3.05} = .93 \quad k_q = \frac{3.0 + 0.77}{3.0 + 0.60} = 1.05$$

The inductance of the reactor is $\frac{3.0}{377} = 0.0077$ henry

Hence, the value of voltage appearing immediately upon interruption, neglecting high frequency oscillations is

$$e_m = 8400 \times \sqrt{2} \times 1.05 \times 0.93 = 11{,}600 \text{ volts}$$

Before settling down, however, the voltage will oscillate between zero and twice that value, the frequency of oscillation being

$$f = \frac{1}{2\,\pi\,\sqrt{.0077 \times 0.008 \times 10^{-6}}}$$

$$= \frac{10^6}{2\,\pi\,\sqrt{.77 \times 0.8}} = 20{,}300 \text{ cycles}$$

The limiting conditions for the high frequency oscillations are as follows:

At time $t = 0$, $e = 0$ and $\frac{d\,e}{d\,t} = 0$

When $t = \infty$, $e = 11{,}600$

These conditions are satisfied by the equation

$$e = 11{,}600\,(1 - \cos 2\,\pi \times 20{,}300\,t)$$

Thus far no attempt has been made to calculate the decrement associated with these oscillations, as this is not as a rule an important factor. In Fig. 10, Part I, this curve is plotted for comparison with the cathode-ray oscillogram obtained on this connection, the decrement exhibited by the oscillation of the cathode-ray oscillogram being assigned to the calculated curve.

Assuming a uniform rate of recovery of dielectric strength of the gap and no decrement, this rate must be that corresponding to the slope of the line $O\,A$ of Fig. 10. That is,

$r = 11{,}600 \times 4.37 \times 20{,}300 \times 10^{-6} = 1070$ volts per microsecond.

2. The recovery voltage of the first phase to clear of a three-phase-to-ground short circuit on an ungrounded generator with three ohms reactance in series per phase.

Generator voltage = 14,500 volts line to line = 8400 volts line to neutral.

External reactance per line = 3.0 ohms at 60 cycles, or 0.0077 henry.

Capacitance to ground between circuit breaker and reactor per phase = 8×10^{-9} farad.

Generator capacitance to ground = 0.8×10^{-6} farad

$$k_\delta = 1.00$$

$$k_g = 1.50$$

$$k_q = \frac{x_q'' + x_e}{x_d'' + x_e} = \frac{0.77 + 3.0}{0.60 + 3.0} = 1.05$$

Hence,

$$e = 1.5 \times 8400 \times \sqrt{2} \times 1.05 = 18{,}700 \text{ volts}$$

For the purpose of determining oscillating characteristics, the circuit may be regarded as that of Fig. 20A, which may be simplified to that of Fig. 20B, and again to that of 20C.

This circuit has two oscillating frequencies, as follows:

$$\frac{1}{2\,\pi}\sqrt{\frac{(3\,C_1 + C_2) + \sqrt{9\,C_1^2 - 2\,C_1\,C_2 + C_2^2}}{2\,L_1\,C_1\,C_2}} = 20{,}300 \text{ cycles}$$

$$\frac{1}{2\,\pi}\sqrt{\frac{(3\,C_1 + C_2) - \sqrt{9\,C_1^2 - 2\,C_1\,C_2 + C_2^2}}{2\,L_1\,C_1\,C_2}} = 2840 \text{ cycles}$$

The mathematics involved in an exact solution for the voltages associated with these frequencies is quite laborious, but a very close approximation to the correct result may be obtained by the following process of reasoning.

The high frequency oscillation is substantially that of inductance L_1 oscillating freely with capacitance C_1, capacitance C_2 acting as a short circuit, while the low frequency oscillation is that of inductance L_2 oscillating freely with capacitance C_2, C_1 being practically an open circuit.

In view of the fact that $L_1 = 2\,L_2$, two-thirds of the final voltage will appear across L_1 and one-third across L_2. Therefore, two-thirds of the final voltage is associated with the high frequency oscillation and one-third with the low frequency oscillation, and the equation of recovery voltage is

$$e = 12{,}500\,(1 - \cos 2\,\pi \times 20{,}300\,t) + 6300\,(1 - \cos 2\,\pi \times 2840\,t)$$

In Fig. 11 this curve is plotted alongside a cathode-ray oscillogram taken on the circuit for which the curve was calculated. As in Case 1, the decrement was not calculated for either frequency, but the high frequency decrement was taken from the cathode ray oscillogram and the low frequency oscillation is plotted without decrement.

3. The recovery voltage of the first phase to clear of a three-phase ungrounded short circuit at the generator terminals.

Generator voltage = 14,500 volts line to line, 8400 volts line to neutral.

$$x_d'' = 0.50 \text{ ohm}$$
$$x_q'' = 0.55 \text{ ohm}$$
$$L_q'' = 0.00146 \text{ henry per phase}$$

Generator capacitance = 0.26×10^{-6} farad per phase.

From Equation (18) the value of voltage appearing immediately, neglecting high frequency oscillations, is

$$e_m = 1.5 \times 8400 \times \sqrt{2} \times \frac{0.55}{0.50} = 19{,}500 \text{ volts}$$

Before settling down, however, the voltage will oscillate between zero and twice that value, the frequency of oscillation being

$$f = \frac{10^4}{4\sqrt{.26 \times .146}} = 12{,}800 \text{ cycles}$$

Assuming that all harmonics are obliterated by the discontinuities of the circuit, we have

$$e = 19{,}500\,(1 - \cos 2\,\pi \times 12{,}800\,t)$$

Assuming a uniform rate of recovery of dielectric strength of the gap, this rate must be

$r = 19{,}500 \times 4.55 \times 12{,}800 \times 10^{-6} = 1135$ volts per microsecond.

4. The recovery voltage of a single-phase to ground short circuit 50,000 ft. (approximately 10 miles) out on a transmission line; circuit breaker directly connected to the high side of the transformer; transformer neutral solidly grounded; low-voltage side of transformer connected to an infinite bus.

Surge impedance of the transmission line = 400 ohms

Velocity of propagation on transmission line = 1,000 ft./microsecond.

Reactance of transmission line = 0.15 ohm/1,000 ft. or 7.5 ohms total.

System voltage = 66,000 volts line to line = 38,100 volts line to ground.

Transformer reactance = 10 per cent on 20,000 kv-a. at 38,100 volts = 7.25 ohms.

$$\text{Short-circuit current} = \frac{38{,}100}{14.75} = 2{,}580 \text{ amperes.}$$

Capacitance of bus structure between circuit breaker and transformer = 0.

Transformer and circuit breaker bushing capacitances = 0.1×10^{-9} farad each.

Effective transformer winding capacitance to ground = 1×10^{-9} farad.

Leakage inductance of transformer winding = 0.0192 henry.

In this case the voltage across the switch will have two components, for the voltage of the line side of the breaker will experience a change of one polarity on account of the negative current suddenly impressed on the transmission line, and the voltage of the transformer side will experience a change of the opposite polarity due to the negative current suddenly impressed on the transformer circuit.

The rate of change of current at the current zero is

$$\frac{d\,i}{d\,t} = 2.58 \times 0.377 \times \sqrt{2} = 1.375 \text{ amperes per microsecond.}$$

The rate of change of voltage on the line side of the breaker is, therefore,

$$\frac{d\,e_1}{d\,t} = 1.375 \times 400 = 550 \text{ volts per microsecond.}$$

This rate of change will continue until the wave has had time to travel to the end of the line and back, at which time it will reverse. At the time of reversal the voltage due to this effect will be $e_1 = 550 \times 100 = 55{,}000$ volts.

On the transformer side of the breaker the circuit consists of a capacitance of 1.2×10^{-9} farad in parallel with an inductance of 0.0192 henry. Impressing suddenly upon such a circuit a current starting from zero and increasing at the rate of 1.375×10^6 amperes per second gives a voltage oscillation

$$e_2 = 1.375 \times 10^6 \times 0.0192 \left(1 - \cos \frac{10^6 \times t}{\sqrt{19.2 \times 1.2}}\right)$$
$$= 26{,}400\,(1 - \cos 2\,\pi \times 33{,}000\,t)$$

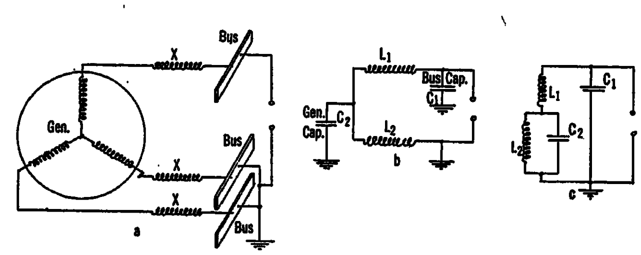

Fig. 20—Successive Simplifications of the Circuit for Analysis of the High-Frequency Oscillations of the Recovery Voltage of a Three-Phase-to-Ground Short Circuit on an Ungrounded Generator with External Reactance in Series

The equation for the voltage across the breaker is then

$$e = 550 \times 10^6\,t + 26{,}400\,(1 - \cos 2\,\pi \times 33{,}000\,t)$$

and the necessary rate of recovery of dielectric strength in the breaker is

$r = 550 + 26{,}400 \times 4.37 \times 33{,}000 \times 10^{-6} = 4510$ volts per microsecond.

The calculated recovery voltage curve is plotted as curve No. 2 of Fig. 8 assuming a decrement $\epsilon^{-10{,}000t}$ for the transformer oscillation. It is interesting to note that this curve has two components of frequencies so different that the highest value of voltage is much lower than the sum of the two components. This may often hold true in the case of a short circuit out on a transmission line, but it will not always be the case.

5. Single-phase-to-ground short circuit at trans-

mission line side of circuit breaker; a second transmission line 50,000 ft. (approximately 10 miles) long is connected between the circuit breaker and the transformer and is open circuited at the far end; transformer neutral is solidly grounded; low side of transformer is connected to an infinite bus.

Constants of transformer and transmission line will be assumed the same as in case 4.

The bushing and transformer capacitances are now negligible, however.

$$\text{Short-circuit current} = \frac{38{,}100}{7.25} = 5{,}260 \text{ amperes.}$$

In this case there will be no voltage change at the line side of the breaker.

On the transformer side of the breaker the voltage may be calculated from circuit (3) of Fig. 8, assuming a current

$$i = 5260 \times 377 \times \sqrt{2}\, t = 2.80 \times 10^6\, t$$

The following equation holds for circuit (3) of Fig. 8 until reflections appear from the far end of the line.

$$\frac{d\,i}{d\,t} = \frac{e}{L} + \frac{1}{Z}\,\frac{d\,e}{d\,t}$$

where Z is the surge impedance of the transmission line, or, solving for e,

$$e = L\frac{d\,i}{d\,t}\left(1 - \epsilon^{-\frac{Z}{L}t}\right)$$

and making the numerical substitutions

$$e = 0.0192 \times 2.80 \times 10^6 \left(1 - \epsilon^{\frac{-400}{.0192}t}\right)$$

$$= 53{,}700\,(1 - \epsilon^{-0.0208t})$$

(t expressed in microseconds)

This equation holds for the voltage at the transformer side of the circuit breaker until the reflected wave returns from the end of the transmission line and also for the front of the wave traveling down the line.

At 100 microseconds, however, the front of the reflected wave returns from the end of the line and there arises at the breaker terminal, over and above the voltage e_0, a voltage which may be calculated by the conventional transmission line theory.

This voltage is

$$e_1 = 2240\,(t - 100)\,\epsilon^{-0.0208\,(t-100)}$$

(t expressed in microseconds)

From $t = 100$ to $t = 200$ microseconds, $e = e_0 + e_1$. At 200 microseconds, however, the front of the next reflection returns from the end of the line and the voltage curve has another hump. The calculated recovery voltage curve for the first 300 microseconds is shown as curve 3 of Fig. 8.

A recovery rate of dielectric strength, $r = 53{,}700 \times 0.0208 = 1120$ volts per microsecond is rapid enough to prevent breakdown. This is only about one-fourth of what was required in case 4, in spite of the fact that the short-circuit current in case 5 is more than twice as great as in case 4.

Interruption of Line Charging Currents

In Part I there is described a process of breakdown of gap insulation, reversal of the potential difference between transformer terminal and transmission line, and interruption of the arc, leaving the line charged up to its new potential; the process repeating itself and increasing the transmission line potential to ground with each repetition.

This section inquires into the wave shape of current and voltage build-up in the transmission line and the rate of recovery voltage rise across the gap at the time the transient charging current supposedly reaches zero and is extinguished.

Fig. 21 applies to the interruption of the charging current of a transmission line when that transmission line is the only apparatus connected to the high side of the transformer. It is a calculated record of voltages and currents immediately after a breakdown of gap

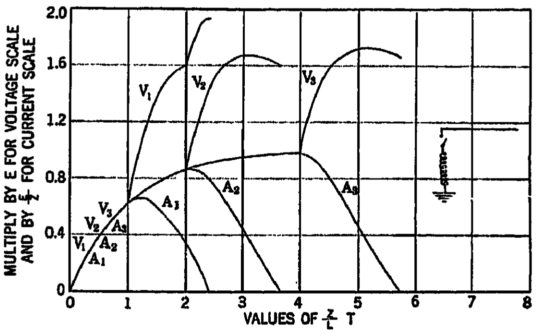

Fig. 21—Current and Voltage Surges upon the Sudden Connection of a Transmission Line to the High Side of a Transformer when no Other Line is Connected There

insulation in the circuit breaker. The curves V_1, V_2, and V_3 of this figure represent the difference between the potential of the line at any instant and its potential just before the breakdown of the gap. The curves A_1, A_2, and A_3 represent the current flowing through the gap at any instant. Curves V_1 and A_1 apply to a line whose length is such that a wave can travel from one end of it to the other and back in a time equal to the time constant of a simple circuit consisting of resistance and inductance alone, whose resistance is equal to the surge impedance of the transmission line and whose inductance corresponds to the reactance which would limit single-phase line-to-ground short-circuit current fed by the transformer into a fault at its high side terminal. Curves V_2 and A_2 apply to a line twice as long as that to which V_1 and A_1 apply, and curves V_3 and A_3 to a line twice as long as that to which V_2 and A_2 apply. All six curves start together from the origin and separate only at the time when reflections return from the far end of the line.

For a transformer whose voltage and kv-a. ratings are 76-kv. to ground (132-kv. line-to-line) and 20,000-kv-a. per phase, operating solidly grounded and with a

single-phase total circuit reactance of 20 per cent at 60 cycles, curves V_1 and A_1 apply to a line 47.5 mi. long, V_2 and A_2 apply to a line 95 mi. long, and V_3 and A_3 to a line 190 mi. long. If the single-phase short-circuit reactance effective at the high side of the transformer is lower than assumed here due to lower voltage, higher kv-a. rating of transformer, more than one transformer in parallel, or a lower per cent circuit reactance, the lengths of line corresponding to the various curves would be proportionately reduced; thus if the voltage were 38-kv. line to ground or the single-phase circuit reactance 5 per cent on 20,000 kv-a. or 20 per cent on 80,000 kv-a., the lengths of line would be reduced to 12, 24, and 48 mi.

The equations for the curves are

1. For the voltage and current up to the time of the first reflection

$$e = E\left(1 - \epsilon^{-\frac{Z}{L}t}\right)$$

$$i = \frac{E}{Z}\left(1 - \epsilon^{-\frac{Z}{L}t}\right)$$

2. For the changes in voltage and current arising from the first reflection

$$e = 2\frac{Z}{L}\, t\, \epsilon^{-\frac{Z}{L}t}\, E$$

$$i = \frac{E}{Z}\left[2 - 2\,\epsilon^{-\frac{Z}{L}t} - 2\frac{Z}{L}\, t\, \epsilon^{-\frac{Z}{L}t}\right]$$

3. For the changes in voltage and current arising from the second reflection

$$e = E\left(2\frac{Z}{L}\, t\, \epsilon^{-\frac{Z}{L}t} - 2\left(\frac{Zt}{L}\right)^2 \epsilon^{-\frac{Z}{L}t}\right)$$

$$i = \frac{E}{Z}\left[-2 + 2\,\epsilon^{-\frac{Z}{L}t} + 2\frac{Z}{L}\, t\, \epsilon^{-\frac{Z}{L}t} + 2\left(\frac{Z}{L}t\right)^2 \epsilon^{-\frac{Z}{L}t}\right]$$

where

E = the potential difference across the circuit breaker just prior to breakdown of the gap.

Z = the surge impedance of the transmission line.

L = the inductance corresponding to the reactance limiting the line-to-ground short-circuit current fed by the transformer into a fault at its high side terminal, and

t = is time in seconds measured from the breakdown of the gap in case (1) and from the initial appearance of the reflections referred to in cases (2) and (3).

The recovery voltage characteristic at the end of the first loop of the high frequency transient current is similar to that of curve No. 2 of Fig. 8 except that the half amplitude of each component, instead of being about half of normal crest voltage is between 0.6 E and E, and E may be several times normal crest voltage, so that as far as rate of recovery voltage rise alone is concerned, the interruption may be much more difficult at this time than under any short-circuit condition. The conditions existing inside the breaker, however, are probably more favorable to interruption than in the short-circuit case, for in this case a moderate current has been flowing in the arc for a time less than one thousandth of a second (for a line less than 100 miles long) and the quantity of gas generated should be very small.

It is conceivable that the limit of the ability of the breaker to interrupt this transient current might limit the line overvoltage, for if this transient charging current is allowed to flow back and forth until it dies away, the transmission line will be brought, in approximately a steady-state condition, to the normal transformer voltage and the process of building up an overvoltage will have to start over again at the beginning. Now it

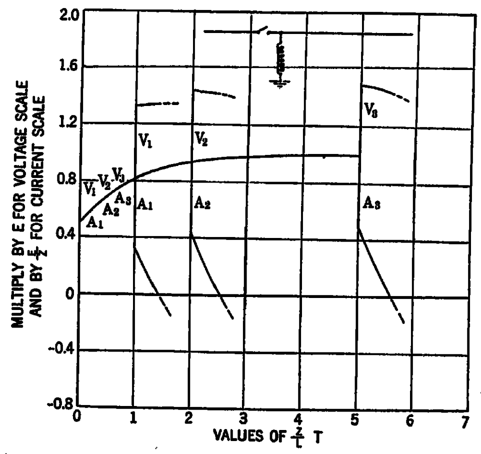

FIG. 22—CURRENT AND VOLTAGE SURGES OCCURRING UPON THE SUDDEN CONNECTION OF A TRANSMISSION LINE TO A POINT TO WHICH ARE CONNECTED THE HIGH SIDE TERMINAL OF A TRANSFORMER AND ONE OTHER LINE LONGER THAN THE ONE SUDDENLY CONNECTED

will probably not make much headway, due to the fact that a considerable gap will have been established between the circuit-breaker contacts.

Fig. 22 applies to the disconnection of a line energized from a bus to which one other line, longer than the one being deenergized, is connected.

The equations for the curves of Fig. 22 are

(1) for the voltage and current up to the time of the first reflection

$$e = E\left(1 - \frac{1}{2}\,\epsilon^{-\frac{Z}{2L}t}\right)$$

$$i = \frac{E}{Z}\left(1 - \frac{1}{2}\,\epsilon^{-\frac{Z}{2L}t}\right)$$

(2) for the changes in voltage and current due to the first reflection

$$e = E\left(\frac{1}{2}\,\epsilon^{-\frac{Z}{2L}t} + \frac{1}{2}\,\frac{Z}{2L}\,t\,\epsilon^{-\frac{Z}{2L}t}\right)$$

$$i = \frac{E}{Z}\left(2 - \frac{3}{2}\,\epsilon^{-\frac{Z}{2L}t} - \frac{1}{2}\,\frac{Z}{2L}\,t\,\epsilon^{-\frac{Z}{2L}t}\right)$$

With E equal to normal crest voltage, the rate of change of current through the switch at the time when the current passes through zero is approximately equal to the rate of change at a current zero of a dead short circuit at the high side terminal of the transformer.

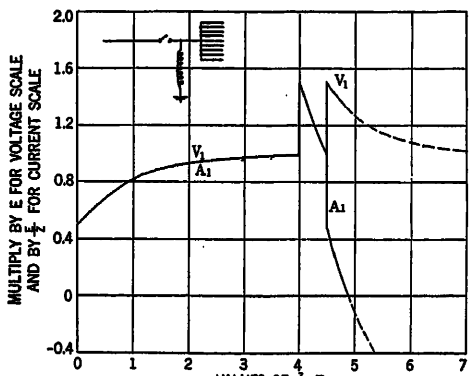

Fig. 23—Current and Voltage Surges Arising Upon the Sudden Connection of a Transmission Line to a Point to Which Are Already Connected the High Side Terminal of a Transformer and Another Line, Slightly Shorter Than the One Suddenly Connected, and Connected to an Infinite Bus at Its Far End

The impedance offered to high frequency transients passing through the switch is approximately a resistance equal to the sum of the surge impedances of the two transmission lines.

With E equal to normal crest voltage, therefore, the rate of rise of recovery voltage is roughly twice that given by the first part of curve 3, Fig. 8. E may, however, become several times normal crest voltage, so that the rate of rise of recovery voltage may reach 6 or 8 times that of curve 3.

From the point of view of the rate of rise of recovery voltage, therefore, interruption at the end of the first loop of this high frequency transient current is several times more difficult than the interruption of short-circuit current for the circuit of curve 3 Fig. 8, and probably about on a par with curve 1 of Fig. 8. The charging transient on this circuit is therefore considerably easier to interrupt than that of Fig. 21.

The remarks with regard to the condition of the gap which were offered in connection with the circuit of Fig. 21 also apply to the condition of the gap for this interruption.

Fig. 23 presents the voltage and current curves for a case differing from that of Fig. 22 in that the tap transmission line connected to the high-voltage bus is slightly shorter than the line being deenergized and is connected to an infinite bus at the far end.

The rate of change of current at the end of the first loop of the high frequency transient is nearly double that occurring in Fig. 22 and the rate of rise of recovery voltage is correspondingly greater.

Fig. 24 presents curves for the disconnection of a transmission line from an infinite bus, neglecting attenuation of the wave front. In this case it will be noted that the current passes through zero with an infinite rate of change. If the current is interrupted under the assumption of zero attenuation the voltage across the switch will rise immediately to a value E. Under this condition it is difficult to see how an interruption could occur. Actually, however, there will be a certain amount of attenuation which in long lines will probably be sufficient to make an interruption possible; in the case of short lines, two or three oscillations may occur before interruption. In this case interruption might occur with the transmission line charged to the same potential as before the breakdown of the gap, and in that case the process of voltage build-up would probably cease, for subsequent voltages across the gap would be only slightly greater than the value of E for this last breakdown.

Acknowledgment

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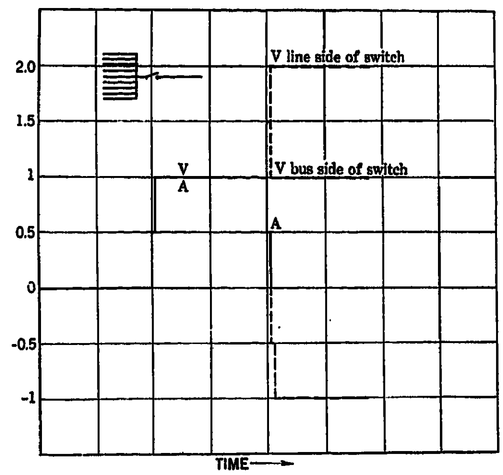

Fig. 24—Current and Voltage Surges Arising Upon the Sudden Connection of a Transmission Line to an Infinite Bus

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Appendix A

In this appendix are calculated the impedances met by the negative current arising upon interruption of short circuits such that the short-circuit current is limited principally by stationary apparatus. Calculations are presented for three-phase short circuits and for two-phase-to-ground short circuits.

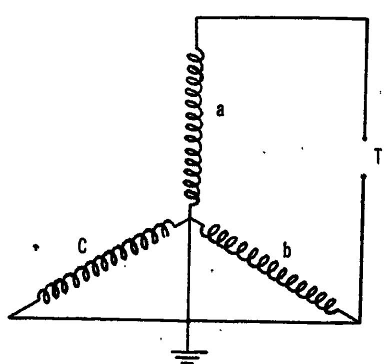

FIG. 25—CIRCUIT FOR THE FIRST PHASE TO CLEAR OF A THREE-PHASE SHORT CIRCUIT

These impedances are determined by the method of symmetrical phase-sequence components as follows:

For a three-phase short circuit, the circuit is that shown in Fig. 25. The impedance of this circuit may be determined by assuming unit current flowing from one terminal to the other and calculating the resulting voltage. The equations applying are

$$e_b = a\, i_1 z_1 + a^2 i_2 z_2 + i_0 z_0 = 0 \qquad \text{(A-1)}$$

$$e_c = a^2 i_1 z_1 + a\, i_2 z_2 + i_0 z_0 = 0 \qquad \text{(A-2)}$$

$$i_a = i_1 + i_2 + i_0 = 1 \qquad \text{(A-3)}$$

Solving these three equations for i_1, i_2, and i_0,

$$i_1 = \frac{\begin{vmatrix} 0 & a^2 z_2 & z_0 \\ 0 & a\, z_2 & z_0 \\ 1 & 1 & 1 \end{vmatrix}}{\begin{vmatrix} a\, z_1 & a^2 z_2 & z_0 \\ a^2 z_1 & a\, z_2 & z_0 \\ 1 & 1 & 1 \end{vmatrix}}$$

$$= \frac{(a^2 - a)\, z_2 z_0}{(a^2 - a)\,(z_1 z_2 + z_2 z_0 + z_0 z_1)}$$

$$= \frac{z_2 z_0}{z_1 z_2 + z_2 z_0 + z_0 z_1} \qquad \text{(A-4)}$$

$$i_2 = \frac{\begin{vmatrix} a\, z_1 & 0 & z_0 \\ a^2 z_1 & 0 & z_0 \\ 1 & 1 & 1 \end{vmatrix}}{\begin{vmatrix} a\, z_1 & a^2 z_2 & z_0 \\ a^2 z_1 & a\, z_2 & z_0 \\ 1 & 1 & 1 \end{vmatrix}}$$

$$= \frac{(a^2 - a)\, z_1 z_0}{(a^2 - a)\,(z_1 z_2 + z_2 z_0 + z_0 z_1)}$$

$$= \frac{z_1 z_0}{z_1 z_2 + z_2 z_0 + z_0 z_1} \qquad \text{(A-5)}$$

$$i_0 = \frac{\begin{vmatrix} a\, z_1 & a^2 z_2 & 0 \\ a^2 z_1 & a\, z_2 & 0 \\ 1 & 1 & 1 \end{vmatrix}}{\begin{vmatrix} a\, z_1 & a^2 z_2 & z_0 \\ a^2 z_1 & a\, z_2 & z_0 \\ 1 & 1 & 1 \end{vmatrix}}$$

$$= \frac{(a^2 - a)\, z_1 z_2}{(a^2 - a)\,(z_1 z_2 + z_2 z_0 + z_0 z_1)}$$

$$= \frac{z_1 z_2}{z_1 z_2 + z_2 z_0 + z_0 z_1} \qquad \text{(A-6)}$$

But

$$z = e_T = e_a = i_1 z_1 + i_2 z_2 + i_0 z_0 = \frac{3\, z_1 z_2 z_0}{z_1 z_2 + z_2 z_0 + z_0 z_1} \qquad \text{(A-7)}$$

And, since $i = \dfrac{E}{z_1}$,

$$e = E \frac{z_2 z_0}{z_1 z_2 + z_2 z_0 + z_0 z_1} \qquad \text{(A-8)}$$

This equation may be used for solidly grounded systems, for systems grounded through a neutral impedance, and for ungrounded systems, for either grounded or ungrounded short circuits by adjusting the value of z_0 as follows:

For grounded short circuits

If the system is solidly grounded use the value of z_0 as calculated for the system at the point of short circuit.

At all points of the system where there is a neutral impedance, add three times the neutral impedance to the value of z_0 for a solidly grounded neutral.

If the system is ungrounded, $z_0 = \infty$

For all ungrounded short circuits, $z_0 = \infty$.

For a two-phase-to-ground short circuit, the circuit is that shown in Fig. 26. The following equations apply to this circuit:

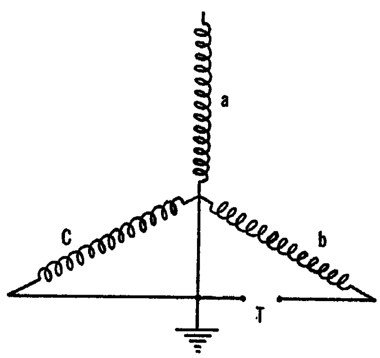

FIG. 26—CIRCUIT FOR THE FIRST PHASE TO CLEAR OF A TWO-PHASE-TO-GROUND SHORT CIRCUIT

$$i_a = i_1 + i_2 + i_0 = 0 \qquad \text{(A-9)}$$

$$i_b = a\, i_1 + a^2 i_2 + i_0 = 1 \qquad \text{(A-10)}$$

$$e_c = a^2 i_1 z_1 + a\, i_2 z_2 + i_0 z_0 = 0 \qquad \text{(A-11)}$$

Solving for i_1, i_2, and i_0,

$$i_1 = \frac{\begin{vmatrix} 0 & 1 & 1 \\ 1 & a^2 & 1 \\ 0 & a z_2 & z_0 \end{vmatrix}}{\begin{vmatrix} 1 & 1 & 1 \\ a & a^2 & 1 \\ a^2 z_1 & a z_2 & z_0 \end{vmatrix}}$$

$$= \frac{a z_2 - z_0}{(a^2 - a)(z_1 + z_2 + z_0)} \qquad \text{(A-12)}$$

$$i_2 = \frac{\begin{vmatrix} 1 & 0 & 1 \\ a & 1 & 1 \\ a^2 z_1 & 0 & z_0 \end{vmatrix}}{\begin{vmatrix} 1 & 1 & 1 \\ a & a^2 & 1 \\ a^2 z_1 & a z_2 & z_0 \end{vmatrix}}$$

$$= \frac{z_0 - a^2 z_1}{(a^2 - a)(z_1 + z_2 + z_0)} \qquad \text{(A-13)}$$

$$i_0 = \frac{\begin{vmatrix} 1 & 1 & 0 \\ a & a^2 & 1 \\ a^2 z_1 & a z_2 & 0 \end{vmatrix}}{\begin{vmatrix} 1 & 1 & 1 \\ a & a^2 & 1 \\ a^2 z_1 & a z_2 & z_0 \end{vmatrix}}$$

$$= \frac{a^2 z_1 - a z_2}{(a^2 - a)(z_1 + z_2 + z_0)} \qquad \text{(A-14)}$$

But

$$z = e_T = e_b = a\, i_1 z_1 + a^2 i_2 z_2 + i_0 z_0$$

$$= \frac{(a^2 - a)(z_1 z_2 + z_2 z_0 + z_0 z_1)}{(a^2 - a)(z_1 + z_2 + z_0)} = \frac{z_1 z_2 + z_2 z_0 + z_0 z_1}{z_1 + z_2 + z_0} \qquad \text{(A-15)}$$

The short-circuit current flowing previous to interruption in the circuit of Fig. 26 is determined by solution of the following equations:

$$e_b = a(E - i_1 z_1) - a^2 i_2 z_2 - i_0 z_0 = 0 \qquad \text{(A-16)}$$

$$e_c = a^2 (E - i_1 z_1) - a\, i_2 z_2 - i_0 z_0 = 0 \qquad \text{(A-17)}$$

$$i_a = i_1 + i_2 + i_0 = 0 \qquad \text{(A-18)}$$

Equations (A-16) and (A-17) may be rewritten

$$a\, i_1 z_1 + a^2 i_2 z_2 + i_0 z_0 = a E \qquad \text{(A-19)}$$

and

$$a^2 i_1 z_1 + a\, i_2 z_2 + i_0 z_0 = a^2 E \qquad \text{(A-20)}$$

From Equations (A-18), (A-19), and (A-20)

$$i_1 = \frac{\begin{vmatrix} 0 & 1 & 1 \\ a E & a^2 z_2 & z_0 \\ a^2 E & a z_2 & z_0 \end{vmatrix}}{\begin{vmatrix} 1 & 1 & 1 \\ a z_1 & a^2 z_2 & z_0 \\ a^2 z_1 & a z_2 & z_0 \end{vmatrix}}$$

$$= \frac{(a^2 - a) E (z_0 + z_2)}{(a^2 - a)(z_1 z_2 + z_2 z_0 + z_0 z_1)}$$

$$= E \frac{z_0 + z_2}{z_1 z_2 + z_2 z_0 + z_0 z_1} \qquad \text{(A-21)}$$

$$i_2 = \frac{\begin{vmatrix} 1 & 0 & 1 \\ a z_1 & a E & z_0 \\ a^2 z_1 & a^2 E & z_0 \end{vmatrix}}{\begin{vmatrix} 1 & 1 & 1 \\ a z_1 & a^2 z_2 & z_0 \\ a^2 z_1 & a z_1 & z_0 \end{vmatrix}}$$

$$= \frac{(a - a^2) E z_0}{(a^2 - a)(z_1 z_2 + z_2 z_0 + z_0 z_1)}$$

$$= E \frac{- z_0}{z_1 z_2 + z_2 z_0 + z_0 z_1} \qquad \text{(A-22)}$$

$$i_0 = \frac{\begin{vmatrix} 1 & 1 & 0 \\ a\,z_1 & a^2 z_2 & a\,E \\ a^2 z_1 & a\,z_2 & a^2 E \end{vmatrix}}{\begin{vmatrix} 1 & 1 & 1 \\ a\,z_1 & a^2 z_2 & z_0 \\ a^2 z_1 & a\,z_2 & z_0 \end{vmatrix}}$$

$$= \frac{(a - a^2)\,E\,z_2}{(a^2 - a)\,(z_1 z_2 + z_2 z_0 + z_0 z_1)}$$

$$= E \frac{-\,z_2}{z_1 z_2 + z_2 z_0 + z_0 z_1} \qquad \textbf{(A-23)}$$

$$i_b = a\,i_1 + a^2 i_2 + i_0 = E\,\frac{(a - a^2)\,z_0 + (a - 1)\,z_2}{z_1 z_2 + z_2 z_0 + z_0 z_1}$$

$$= (a - a^2)\,E\,\frac{z_0 - a^2 z_2}{z_1 z_2 + z_2 z_0 + z_0 z_1} \qquad \textbf{(A-24)}$$

The magnitude of the vector i_b is given by

$$|\,i_b\,| = \sqrt{3}\,E\,\frac{\sqrt{z_0^2 + z_0 z_2 + z_2^2}}{z_1 z_2 + z_2 z_0 + z_0 z_1} \qquad \textbf{(A-25)}$$

Thus multiplying Equations (A-15) and (A-25), the magnitude of the recovery voltage of a two-phase-to-ground short circuit in which the effect of the stationary apparatus predominates over the effect of rotating machinery is given by

$$e = \sqrt{3}\,E\,\frac{\sqrt{z_0^2 + z_0 z_2 + z_2^2}}{z_1 + z_2 + z_0} \qquad \textbf{(A-26)}$$

Appendix B

The object of this appendix is the determination of the expression for the magnitude of recovery voltage, (neglecting the high frequency considerations), for a synchronous machine in which x_q'' differs from x_d'' and in a system in which the short circuit is opened before the direct-current component has vanished.

As in the remainder of the paper, the principle of superposition is used here. The voltage across the terminals of the switch is calculated as that which would be necessary to force through the circuit from one switch terminal to the other, the current i_a.

The distribution of the current in phases b and c is determined by considering that both i_b and i_c have one component equal to $-\frac{1}{2}\,i_a$, and a second component, which may be considered as a circulating current, which is equal and opposite in phases b and c. Thus the currents in phases b and c may be represented as follows,

$$i_b = i_{b1} + i_{b2} \qquad \textbf{(B-1)}$$

$$i_c = i_{c1} + i_{c2} \qquad \textbf{(B-2)}$$

where,

$$i_{b1} = i_{c1} = -\frac{1}{2}\,i_a$$

and

$$i_{b2} = -\,i_{c2}$$

The current which flows when a symmetrical three-phase ungrounded short circuit is placed on a three-phase machine, is given by Messrs. Doherty and Nickle in their paper *Synchronous Machines V.** The current in phase a which flows previous to interruption can therefore be expressed as,

$$i_a = \frac{e_0}{x_d}\cos(t - \alpha) + e_0\,\frac{x_d - x_d'}{x_d\,x_d'}\,\epsilon^{-\sigma_{f1} t}\cos(t - \alpha) + e_0\,\frac{x_d' - x_d''}{x_d'\,x_d''}\,\epsilon^{-\sigma_{f2} t}\cos(t - \alpha) - e_0\,\frac{x_d'' + x_q''}{2\,x_d''\,x_q''}\,\epsilon^{-\sigma_a t}\cos\alpha + e_0\,\frac{x_d'' - x_q''}{2\,x_d''\,x_q''}\,\epsilon^{-\sigma_a t}\cos(2\,t - \alpha) \qquad \textbf{(B-3)}$$

where

e_0 = open circuit terminal voltage before short circuit.

α = displacement between armature winding axis and axis of field pole at the instant of short circuit.

x_d = three-phase line-to-neutral synchronous reactance, direct axis.

x_d' = three-phase line-to-neutral transient reactance, direct axis.

x_d'' = three-phase line-to-neutral subtransient reactance, direct axis.

x_q = three-phase line-to-neutral synchronous reactance, quadrature axis.

x_q'' = three-phase line-to-neutral subtransient reactance, quadrature axis.

σ_a and σ_f are the decrement factors of the armature circuit and the field circuit with the armature short-circuited.

By making a change of reference axis, and by collecting the first and second terms, the current in phase a, under short-circuit conditions may be expressed as follows:

$$i_a = k_\delta\left[\frac{\cos\theta}{x_d''} - B\,\delta\cos\phi + C\,\delta\cos(2\,\theta + \phi)\right] \qquad \textbf{(B-4)}$$

where,

$$k_\delta = \frac{i}{i''}$$

$$\delta = \frac{e^{-\sigma_a t}}{k_\delta}$$

*A. I. E. E. Trans., 1930, Vol. XLIX, R. E. Doherty and C. A. Nickle.

θ = time (numerically equal to radians), and is measured as the displacement in the direction of rotation of the direct axis of the field from the axis of magnetization of phase a.

ϕ = displacement of the axis of the field from the axis of phase a at the instant of short circuit.

$$B = \frac{x_d'' + x_q''}{2\, x_d''\, x_q''}$$

$$C = \frac{x_d'' - x_q''}{2\, x_d''\, x_q''}$$

In the following analysis, k_δ is omitted. Its effect may be considered by applying it to the final results.

To obtain the voltages generated by the interruption of the current represented by Equation (**B-4**), a current equal and opposite is assumed to flow in phase a, and the currents in phases b and c are considered split into two components as given by Equations (**B-1**) and (**B-2**). It is convenient then, to calculate the voltages in two parts, the first part being that arising from i_a, i_{b1}, and i_{c1}, and the second part being that arising from i_{b2} and i_{c2}. Accordingly, the voltages across phases at a, b, and c may be represented as:

$$e_a = e_{a1} + e_{a2} \quad \textbf{(B-5)}$$

$$e_b = e_{b1} + e_{b2} \quad \textbf{(B-6)}$$

$$e_c = e_{c1} + e_{c2} \quad \textbf{(B-7)}$$

The flux linkages of phases a, b, and c due to the currents i_a, i_b, and i_c, may be calculated by the expressions given by Messrs. Park and Robertson in their paper *The Reactances of Synchronous Machines.** Since the neutral is ungrounded, the per unit linkages in phases a, b, and c may be represented as follows,

$$\psi_a = -\frac{x_d'' + x_q''}{3}\left[i_a - \frac{i_b + i_c}{2}\right] - \frac{x_d'' - x_q''}{3}\left[i_a \cos 2\,\theta + i_b \cos(2\,\theta - 120) + i_c \cos(2\,\theta + 120)\right] \quad \textbf{(B-8)}$$

$$\psi_b = -\frac{x_d'' + x_q''}{3}\left[i_b - \frac{i_c + i_a}{2}\right] - \frac{x_d'' - x_q''}{3}\left[i_a \cos(2\,\theta - 120) + i_b \cos(2\,\theta + 120) + i_c \cos 2\,\theta\right] \quad \textbf{(B-9)}$$

$$\psi_c = -\frac{x_d'' + x_q''}{3}\left[i_c - \frac{i_a + i_b}{2}\right] - \frac{x_d'' - x_q''}{3}\left[i_a \cos(2\,\theta + 120) + i_b \cos 2\,\theta + i_c \cos(2\,\theta - 120)\right] \quad \textbf{(B-10)}$$

*R. H. Park and B. L. Robertson, A. I. E. E. TRANS., 1928, Vol. XLVII, p. 514.

To facilitate calculation let

$$A = \frac{x_d'' + x_q''}{3}$$

and

$$D = \frac{x_d'' - x_q''}{3}$$

and

$$k_q = \frac{x_q''}{x_d''}$$

By letting i_a in Equation (**B-8**) be equal to the negative of the value given by Equation (**B-4**), and letting i_{b1} and i_{c1} equal minus one-half i_a, the expression for flux linkages in phase a due to the currents i_a, i_{b1} and i_{c1} may be written:

$$\psi_{a1} = \frac{(3 + k_q)}{4}\cos\theta + \frac{(1 - k_q^2)}{4\,k_q}\cos(2\,\theta + \phi) - \frac{\delta}{4}\,\frac{(1 - k_q^2)}{k_q}\cos\phi\cos 2\,\theta + \frac{(1 - k_q)}{4}\cos 3\,\theta + \frac{\delta\,(1 - k_q)^2}{8\,k_q}\cos(4\,\theta + \phi) + \frac{\delta\,(1 + k_q)^2}{4\,k_q}\cos\phi + \frac{\delta\,(1 - k_q)^2}{8\,k_q}\cos\phi \quad \textbf{(B-11)}$$

The voltage due to these flux linkages is:

$$\frac{d\,\psi_{a1}}{d\,t} = e_{a1} = -\frac{(3 + k_q)}{4}\sin\theta - \frac{\delta}{2\,k_q}(1 - k_q^2)\sin\phi\cos 2\,\theta - \frac{3\,(1 - k_q)}{4}\sin 3\,\theta - \frac{\delta\,(1 - k_q)^2}{2\,k_q}\sin(4\,\theta + \phi) \quad \textbf{(B-11a)}$$

Likewise, by using Equation (**B-9**), the flux linkages in phase b may be represented as:

$$\psi_{b1} = \frac{(-3 - k_q)}{8}\cos\theta + \frac{\delta}{8\,k_q}(1 - k_q^2)\sin\phi\sin 2\,\theta - \frac{(1 - k_q)}{8}\cos 3\,\theta - \frac{(1 - k_q)^2}{16\,k_q}\delta[\cos\phi - \sqrt{3}\sin\phi]\cos 4\,\theta + \frac{\sqrt{3}}{8}(1 - k_q)\sin\theta - \frac{\sqrt{3}}{8}\,\frac{(1 - k_q^2)}{k_q}\,\delta\cos\phi\sin 2\,\theta + \frac{\sqrt{3}}{8}(1 - k_q)\sin 3\,\theta + \frac{(1 - k_q)^2}{16\,k_q}\delta[\sin\phi + \sqrt{3}\cos\phi]\sin 4\,\theta + \frac{(1 + k_q)^2}{8\,k_q}\delta\cos\phi - \frac{(1 - k_q)^2}{16\,k_q}\delta\cos\phi - \frac{\sqrt{3}}{16}\,\frac{(1 - k_q)^2}{k_q}\delta\sin\phi \quad \textbf{(B-12)}$$

The voltage generated in phase b due to these flux linkages is,

$$\frac{d\,\psi_{b1}}{d\,t} = e_{b1} = \frac{(3+k_q)}{8}\sin\theta + \frac{3\,(1-k_q)}{8}\sin 3\,\theta$$

$$+\frac{(1-k_q)^2\,\delta}{4\,k_q}[\cos\phi - \sqrt{3}\sin\phi]\sin 4\,\theta$$

$$+\frac{\sqrt{3}}{8}(1-k_q)\cos\theta + \frac{(1-k_q^2)\,\delta}{4\,k_q}[\sin\phi - \sqrt{3}\cos\phi]\cos 2\,\theta$$

$$+\frac{3\sqrt{3}}{8}(1-k_q)\cos 3\,\theta + \frac{(1-k_q)^2\,\delta}{4\,k_q}[\sin\phi + \sqrt{3}\cos\phi]\cos 4\,\theta \tag{B-12a}$$

Also the flux linkages in phase c by the use of Equation (**B-10**), may be represented as,

$$\psi_{c1} = \frac{(-3-k_q)}{8}\cos\theta + \frac{(1-k_q^2)}{8\,k_q}\,\delta\sin\phi\sin 2\,\theta$$

$$-\frac{(1-k_q)}{8}\cos 3\,\theta - \frac{(1-k_q)^2}{8\,k_q}\delta[\cos\phi + \sqrt{3}\sin\phi]\cos 4\,\theta$$

$$-\frac{\sqrt{3}}{8}(1-k_q)\sin\theta + \frac{\sqrt{3}}{8\,k_q}(1-k_q^2)\,\delta\cos\phi\sin 2\,\theta$$

$$-\frac{\sqrt{3}}{8}(1-k_q)\sin 3\,\theta + \frac{(1-k_q)^2\,\delta}{16\,k_q}[\sin\phi - \sqrt{3}\cos\phi]\sin 4\,\theta$$

$$+\frac{(1+k_q)^2}{8\,k_q}\,\delta\cos\phi - \frac{(1-k_q)^2}{16\,k_q}\,\delta\cos\phi$$

$$+\frac{\sqrt{3}}{16\,k_q}(1-k_q)^2\,\delta\sin\phi \tag{B-13}$$

The voltage in phase c due to these flux linkages is, therefore,

$$\frac{d\,\psi_{c1}}{d\,t} = e_{c1} = \frac{(3+k_q)}{8}\sin\theta + \frac{3}{8}(1-k_q)\sin 3\,\theta$$

$$+\frac{(1-k_q)^2\,\delta}{4\,k_q}[\cos\phi + \sqrt{3}\sin\phi]\sin 4\,\theta - \frac{3}{8}(1-k_q)\cos\theta$$

$$+\frac{(1-k_q^2)\,\delta}{4\,k_q}[\sin\phi + \sqrt{3}\cos\phi]\cos 2\,\theta - \frac{3\sqrt{3}}{8}(1-k_q)\cos 3\,\theta$$

$$+\frac{(1-k_q)^2\,\delta}{4\,k_q}[\sin\phi - \sqrt{3}\cos\phi]\cos 4\,\theta \tag{B-13a}$$

According to Equations (**B-12**) and (**B-13**) there is a difference between the flux linkages in phase b and the flux linkages in phace c. The second components of current in these phases must be of such magnitude as to give rise to equal and opposite differences in flux linkages between phase b and phase c. The total voltage across phases b and c is obtained by differentiating the sum of the two components of flux linkages in each phase.

The currents i_{b2} and i_{c2} must be of such magnitude as to give rise to a flux difference between phases b and c which is equal and opposite to the flux difference $\psi_{b1}-\psi_{c1}$ which is obtained by subtracting Equation (**B-13**) from Equation (**B-12**).

$$\psi_{b1}-\psi_{c1} = \frac{\sqrt{3}}{4}(1-k_q)\sin\theta - \frac{\sqrt{3}\,\delta}{4\,k_q}(1-k_q^2)\cos\phi\sin 2\,\theta$$

$$+\frac{\sqrt{3}}{4}(1-k_q)\sin 3\,\theta + \frac{\sqrt{3}}{8\,k_q}(1-k_q)^2\,\delta\,[\sin(4\,\theta+\phi)]$$

$$-\frac{\sqrt{3}}{8}\,\frac{(1-k_q)^2}{k_q}\,\delta\sin\phi \tag{B-14}$$

If the second components of flux in phases b and c due to the "circulating" components of current, are represented by ψ_{b2} and ψ_{c2}, the relation between the differences in fluxes between the phases b and c due to the two components in each phase is,

$$\psi_{b1}-\psi_{c1} = -(\psi_{b2}-\psi_{c2}) \tag{B-15}$$

Referring again to Equations (**B-9**) and (**B-10**), the flux linkages in phases b and c due to the circulating current, may be determined by setting $i_{a2}=0$, and $i_{b2}=-i_{c2}$. Thus the expressions for ψ_{b2} and ψ_{c2} are,

$$\psi_{b2} = -\frac{3}{2}A\,i_{b2} - D\,i_{b2}\,\{\cos(2\,\theta+120°) - \cos 2\,\theta\} \tag{B-16}$$

$$\psi_{c2} = +\frac{3}{2}A\,i_{b2} - D\,i_{b2}\,\{\cos 2\,\theta - \cos(2\,\theta-120°)\} \tag{B-17}$$

Likewise, by Equation (**B-8**), the flux linkages in phase a due to the second component of current in phases b and c may be represented as,

$$\psi_{a2} = -\sqrt{3}\,D\,i_{b2}\sin 2\,\theta \tag{B-18}$$

The difference in flux linkages in phase b and c due to the second component of current is:

$$\psi_{b2}-\psi_{c2} = i_{b2}\,\{-3\,A + 3\,D\cos 2\,\theta\} \tag{B-19}$$

By referring to Equation (**B-15**), it is obvious that the right-hand member of Equation (**B-14**) is equal to minus the right-hand member of Equation (**B-19**). This relation may therefore be written,

$$\frac{\sqrt{3}}{4}(1-k_q)\sin\theta - \frac{\sqrt{3}\,\delta}{4\,k_q}(1-k_q^2)\cos\phi\sin 2\,\theta$$

$$+\frac{\sqrt{3}}{4}(1-k_q)\sin 3\,\theta + \frac{\sqrt{3}}{8\,k_q}(1-k_q)^2\,\delta\sin(4\,\theta+\phi)$$

$$-\frac{\sqrt{3}}{8}\,\frac{(1-k_q)^2}{k_q}\,\delta\sin\phi = i_{b2}\,\{3\,A - 3\,D\cos 2\,\theta\} \tag{B-20}$$

Equation (**B-20**) will be solved by letting i_{b2} be equal to a Fourier series and solving for the coefficients.

Thus

$$i_{b2} = \sum_{1}^{\infty} B \sin \theta + \sum_{0}^{\infty} C \cos \theta \qquad \text{(B-21)}$$

By substituting Equation (**B-21**) in Equation (**B-20**) the following sets of equations are obtained by equating coefficients of corresponding terms.

The constant term, C_0 is:

$$C_0 = -\frac{\sqrt{3}}{24\,A}\,\frac{(1-k_q)^2}{k_q}\,\delta \sin \phi + \frac{D\,C_2}{2\,A} \qquad \text{(B-22)}$$

The coefficients of the sine terms are:
$\sin \theta$:

$$\left(3\,A + \frac{3}{2}\,D\right) B_1 - \frac{3}{2}\,D\,B_3 = \frac{\sqrt{3}}{4}\,(1-k_q) \qquad \text{(B-23)}$$

$\sin 2\,\theta$:

$$3\,A\,B_2 - \frac{3}{2}\,D\,B_4 = -\frac{\sqrt{3}\,\delta}{4\,k_q}(1-k_q^2)\cos\phi \qquad \text{(B-24)}$$

$\sin 3\,\theta$:

$$-\frac{3}{2}\,D\,B_1 + 3\,A\,B_3 - \frac{3}{2}\,D\,B_5 = \frac{\sqrt{3}}{4}\,(1-k_q) \qquad \text{(B-25)}$$

$\sin 4\,\theta$:

$$-\frac{3}{2}\,D\,B_2 + 3\,A\,B_4 - \frac{3}{2}\,D\,B_6 = \frac{\sqrt{3}}{8\,k_q}(1-k_q)^2\,\delta \cos\phi \qquad \text{(B-26)}$$

$\sin n\,\theta\ (n > 4)$:

$$-\frac{3}{2}\,D\,B_{(n-2)} + 3\,A\,B_n - \frac{3}{2}\,D\,B_{(n+2)} = 0 \qquad \text{(B-27)}$$

The even coefficients B of the sine terms are zero, and the odd coefficients follow the relation,

$$m = \left.\frac{B_{(n+2)}}{B_n}\right]_{n=3}^{n=\infty} = \frac{(1-k_q^{1/2})^2}{(1-k_q)} \qquad \text{(B-28)}$$

Substituting the relation (**B-28**) in Equations (**B-23**) and (**B-25**), these equations may be solved simultaneously for B_1 and B_3, which are,

$$B_1 = \frac{3\sqrt{3}\,(1-k_q)\left[A - \frac{D}{2}\,(m-1)\right]}{36\,A^2 - 18\,A\,D\,m + 18\,A\,D - 9\,D^2\,m - 9\,D^2} \qquad \text{(B-29)}$$

$$B_3 = \frac{3\sqrt{3}\,(1-k_q)\,[A+D]}{36\,A^2 - 18\,A\,D\,m + 18\,A\,D - 9\,D^2\,m - 9\,D^2} \qquad \text{(B-30)}$$

By substituting Equation (**B-28**) in Equations (**B-24**) and (**B-26**), these equations may be solved simultaneously for B_2 and B_4, which are,

$$B_2 = -\frac{\sqrt{3}\,(1-k_q^2)\,\delta\cos\phi}{12\,A\,k_q} \qquad \text{(B-31)}$$

$${}_4B = 0 \qquad \text{(B-32)}$$

Likewise, by equating coefficients of the corresponding cosine terms, the following relations are obtained.
$\cos \theta$:

$$\left(3\,A - \frac{3}{2}\,D\right) C_1 - \frac{3}{2}\,D\,C_3 = 0 \qquad \text{(B-33)}$$

$\cos 2\,\theta$:

$$-3\,D\,C_0 + 3\,A\,C_2 - \frac{3}{2}\,D\,C_4 = 0 \qquad \text{(B-34)}$$

$\cos 3\,\theta$:

$$3\,A\,C_3 - \frac{3}{2}\,D\,C_5 = 0 \qquad \text{(B-35)}$$

$\cos 4\,\theta$:

$$-\frac{3}{2}\,D\,C_2 + 3\,A\,C_4 - \frac{3}{2}\,D\,C_6 = \frac{\sqrt{3}}{8}\,\frac{(1-k_q)^2}{k_q}\,\delta\sin\phi \qquad \text{(B-36)}$$

$\cos n\,\theta\ (n > 4)$:

$$-\frac{3}{2}\,D\,C_{(n-2)} + 3\,A\,C_n - \frac{3}{2}\,D\,C_{(n+2)} = 0 \qquad \text{(B-37)}$$

The odd coefficients of the cosine series are zero and the even coefficients are satisfied by the following relation,

$$m = \left.\frac{C_{(n+2)}}{C_n}\right]_{n=4}^{n=\infty} = \frac{(1-k_q^{1/2})^2}{(1-k_q)} \qquad \text{(B-38)}$$

Substituting Equation (**B-38**) in Equations (**B-34**) and (**B-36**), and using the value of C_0 in Equation (**B-22**), Equations (**B-34**) and (**B-36**) may be solved simultaneously for C_2 and C_4, as follows,

$$C_2 = -\frac{3\sqrt{3}\,D\,\delta\sin\phi\,(1-k_q)^2\,[A - D\,m]}{4\,k_q\,[36\,A^3 - 18\,A^2\,D\,m - 27\,A\,D^2 + 9\,D^3\,m]} \qquad \text{(B-39)}$$

and

$$C_4 = \frac{3\sqrt{3}\,\delta\sin\phi\,(1-k_q)^2\,[A^2 - D^2]}{2\,k_q\,[36\,A^3 - 18\,A^2\,D\,m - 27\,A\,D^2 + 9\,D^3\,m} \qquad \text{(B-40)}$$

The flux linkages in phase a due to the "circulating" or second component of current in phases b and c may be obtained by using Equation (**B-8**) and the additional conditions that,

$$i_{a2} = 0$$

and

$$i_{b2} = -i_{c2}$$

Thus the expression for flux linkages in phase a due to the second component of current in phases b and c is,

$$\psi_{a2} = -\sqrt{3}\,D\,[C_o + B_2 \sin 2\,\theta + \sum_{n_o=1}^{n_o=\infty} B_{n_o} \sin n_o\,\theta + \sum_{n_e=2}^{n_e=\infty} C_{n_e} \cos n_e\,\theta] \sin 2\,\theta \qquad \text{(B-41)}$$

or

$$\psi_{a2} = -\sqrt{3}\,D\,[C_o \sin 2\theta + B_2 \sin^2 2\theta + \sin 2\theta \sum_{n_o=1}^{n_o=\infty} B_{no} \sin n_o\theta + \sin 2\theta \sum_{n_e=2}^{n_e=\infty} C_{ne} \cos n_e\theta] \quad \text{(B-42)}$$

where n_o = odd term

and n_e = even term

But since,

$$\sin n\theta \sin 2\theta = \frac{\cos(n-2)\theta - \cos(n+2)\theta}{2}$$

and

$$\sin 2\theta \cos n\theta = \frac{\sin(n+2)\theta - \sin(n-2)\theta}{2},$$

Equation (**B-42**) may be written as follows, so that,

$$\psi_{a2} = -\sqrt{3}\,D\left[\frac{B_2}{2} + C_o \sin 2\theta - \frac{B_2}{2}\cos 4\theta + \sum_{n_o=-1}^{n_o=\infty} \frac{B_{(no+2)} \cos n_o\theta}{2} - \sum_{n_o=3}^{n_o=\infty} \frac{B_{(no-2)} \cos n_o\theta}{2} + \sum_{n_e=4}^{n_e=\infty} \frac{C_{(ne-2)} \sin n_e\theta}{2} - \sum_{n_e=0}^{n_e=\infty} \frac{C_{(ne+2)} \sin n_e\theta}{2}\right] \quad \text{(B-43)}$$

The voltage induced in phase a due to the flux linkages caused by the circulating current is,

$$\frac{d\psi_{a2}}{dt} = e_{a2} = -\sqrt{3}\,D\,[2C_0 \cos 2\theta + 2B_2 \cos 4\theta - \sum_{n_o=-1}^{n_o=\infty} \frac{n_o}{2} B_{(no+2)} \sin n_o\theta + \sum_{n_o=3}^{n_o=\infty} \frac{n_o}{2} B_{(no-2)} \sin n_o\theta + \sum_{n_e=4}^{n_e=\infty} \frac{n_e}{2} C_{(ne-2)} \cos n_e\theta - \sum_{n_e=0}^{n_e=\infty} \frac{n_e}{2} C_{(ne+2)} \cos n_e\theta\Big] \quad \text{(B-44)}$$

Equation (**B-9**) may be used to obtain an expression for the flux linkages in phase b due to the circulating current in phases b and c.

$$\psi_{b2} = -\frac{3}{2}A\Big[C_o + B_2 \sin 2\theta + \sum_{n_o=1}^{n_o=\infty} B_{no} \sin n_o\theta + \sum_{n_e=2}^{n_e=\infty} C_{ne} \cos n_e\theta\Big] + \frac{3}{2}D\Big[C_o + B_2 \sin 2\theta + \sum_{n_o=1}^{n_o=\infty} B_{no} \sin n_o\theta + \sum_{n_e=2}^{n_e=\infty} C_{ne} \cos n_e\theta\Big]\cos 2\theta + \frac{\sqrt{3}}{2}D\Big[C_0 + B_2 \sin 2\theta + \sum_{n_o=1}^{n_o=\infty} B_{no} \sin n_o\theta + \sum_{n_e=2}^{n_e=\infty} C_{ne} \cos n_e\theta\Big]\sin 2\theta \quad \text{(B-45)}$$

By expanding Equation (**B-45**), the following expression is obtained,

$$\psi_{b2} = -\frac{3}{2}A\Big[C_0 + B_2 \sin 2\theta + \sum_{n_o=1}^{n_o=\infty} B_{no} \sin n_o\theta + \sum_{n_e=2}^{n_e=\infty} C_{ne} \cos n_e\theta\Big] + \frac{3}{2}D\Big[C_0 \cos 2\theta + \frac{B_2 \sin 4\theta}{2} + \cos 2\theta \sum_{n_o=1}^{n_o=\infty} B_{no} \sin n_o\theta + \cos 2\theta \sum_{n_e=2}^{n_e=\infty} C_{ne} \cos n_e\theta\Big] + \frac{\sqrt{3}}{2}D\Big[C_0 \sin 2\theta + \frac{B_2}{2} - \frac{B_2 \cos 4\theta}{2} + \sin 2\theta \sum_{n_o=1}^{n_o=\infty} B_{no} \sin n_o\theta + \sin 2\theta \sum_{n_e=2}^{n_e=\infty} C_{ne} \cos n_e\theta\Big] \quad \text{(B-46)}$$

Equation (**B-46**) may, by the substitution of trigonometric identities, be written as follows,

$$\psi_{b2} = -\frac{3}{2}A\Big[C_0 + B_2 \sin 2\theta + \sum_{n_o=1}^{n_o=\infty} B_{no} \sin n_o\theta + \sum_{n_e=2}^{n_e=\infty} C_{ne} \cos n_e\theta\Big] + \frac{3}{2}D\Big[C_0 \cos 2\theta + \frac{B_2}{2}\sin 4\theta + \sum_{n_o=3}^{n_o=\infty} \frac{B_{(no-2)}}{2} \sin n_o\theta + \sum_{n_o=-1}^{n_o=\infty} \frac{B_{(no+2)}}{2} \sin n_o\theta + \sum_{n_e=0}^{n_e=\infty} \frac{C_{(ne+2)}}{2} \cos n_e\theta + \sum_{n_e=4}^{n_e=\infty} \frac{C_{(ne-2)}}{2} \cos n_e\theta\Big] + \frac{\sqrt{3}}{2}D\Big[C_0 \sin 2\theta + \frac{B_2}{2} - \frac{B_2}{2}\cos 4\theta + \sum_{n_o=-1}^{n_o=\infty} \frac{B_{(no+2)}}{2} \cos n_o\theta - \sum_{n_o=3}^{n_o=\infty} \frac{B_{(no-2)}}{2} \cos n_o\theta + \sum_{n_e=4}^{n_e=\infty} \frac{C_{(ne-2)}}{2} \sin n_e\theta - \sum_{n_e=0}^{n_e=\infty} \frac{C_{(ne+2)}}{2} \sin n_e\theta\Big] \quad \text{(B-47)}$$

The total flux linkage in phase b may be represented by $(\psi_{b1} + \psi_{b2})$, or equal to the sum of the flux linkages

represented by Equations (**B-12**) and (**B-47**). Thus the total flux linkages in phase b are,

$$\psi_b = \frac{(-3 - k_q)}{8}\cos\theta + \frac{(1-k_q^2)}{8\,k_q}\,\delta\sin\phi\sin 2\theta$$

$$-\frac{(1-k_q)}{8}\cos 3\theta - \frac{(1-k_q)^2}{16\,k_q}\,\delta\cos\phi\cos 4\theta$$

$$+\frac{(1-k_q)^2\,\delta}{16\,k_q}\sin\phi\sin 4\theta + \frac{\sqrt{3}}{2}\,D\,C_0\sin 2\theta$$

$$-\frac{\sqrt{3}}{4}\,D\,B_2\cos 4\theta + \frac{\sqrt{3}}{2}\,D\Bigg[\sum_{n_o=-1}^{n_o=\infty}\frac{B_{(no+2)}}{2}\cos n_o\theta$$

$$-\sum_{n_o=3}^{n_o=\infty}\frac{B_{(no-2)}}{2}\cos n_o\theta + \sum_{n_e=4}^{n_e=\infty}\frac{C_{(ne-2)}}{2}\sin n_e\theta$$

$$-\sum_{n_e=0}^{n_e=\infty}\frac{C_{(ne+2)}}{2}\sin n_e\theta\Bigg] + \frac{(1+k_q)^2\,\delta}{8\,k_q}\cos\phi \qquad \textbf{(B-48)}$$

since,

$$\left[-\frac{3}{4}\,D\,C_{(ne-2)} + \frac{3}{2}\,A\,C_{ne} - \frac{3}{4}\,D\,C_{(ne+2)}\right]\cos 4\theta$$

$$= \frac{\sqrt{3}}{16}\,\frac{(1-k_q)^2}{k_q}\sin\phi\cos 4\theta \qquad \textbf{(B-36)}$$

$$\left[\frac{3}{2}\,A\,B_1 + \frac{3}{4}\,D\,B_1 - \frac{D}{4}\,B_3\right]\sin\theta = \frac{\sqrt{3}}{8}\,(1-k_q)\sin\theta \qquad \textbf{(B-23)}$$

$$\frac{3}{2}\,A\,B_2\sin 2\theta = -\frac{\sqrt{3}}{8}\,\frac{(1-k_q^2)}{k_q}\,\delta\cos\phi\sin 2\theta \qquad \textbf{(B-24)}$$

$$\left[-\frac{3}{4}\,D\,B_1 + \frac{3}{2}\,A\,B_3 - \frac{3}{4}\,D\,B_5\right]\sin 3\theta$$

$$= \frac{\sqrt{3}}{8}\,(1-k_q)\sin 3\theta \qquad \textbf{(B-25)}$$

$$\frac{3}{4}\,D\,B_2\sin 4\theta = -\left[\frac{\sqrt{3}\,(1-k_q)^2}{16\,k_q}\,\delta\cos\phi\sin 4\theta\right] \qquad \textbf{(B-26)}$$

$$\frac{3}{2}\,A\,C_0 = -\frac{\sqrt{3}}{16}\,\frac{(1-k_q)^2}{k_q}\,\delta\sin\phi + \frac{3\,D\,C_2}{4} \qquad \textbf{(B-22)}$$

$$\frac{3}{2}\,D\sum_{n_e=4}^{n_e=\infty}C_{(ne-2)}\cos n_e\theta - \frac{3}{2}\,A\sum_{n_e=4}^{n_e=\infty}C_{ne}\cos n_e\theta$$

$$+\frac{3}{2}\,D\sum_{n_e=4}^{n_e=\infty}\frac{C_{(ne+2)}}{2}\cos n_e\theta = 0 \qquad \textbf{(B-37)}$$

The total voltage induced in phase b is therefore,

$$\frac{d\,\psi_b}{dt} = e_b = \frac{(3+k_q)}{8}\sin\theta + \frac{(1-k_q^2)}{4\,k_q}\,\delta\sin\phi\cos 2\theta$$

$$+\frac{3(1-k_q)}{8}\sin 3\theta + \frac{(1-k_q)^2}{4\,k_q}\,\delta\sin(4\theta+\phi)$$

$$+\sqrt{3}\,D\,C_0\cos 2\theta + \sqrt{3}\,D\,B_2\sin 4\theta$$

$$+\frac{\sqrt{3}}{2}\,D\Bigg[-\sum_{n_o=-1}^{n_o=\infty}\frac{n_o}{2}\,B_{(no+2)}\sin n_o\theta$$

$$+\sum_{n_o=3}^{n_o=\infty}\frac{n_o}{2}\,B_{(no-2)}\sin n_o\theta + \sum_{n_e=4}^{n_e=\infty}\frac{n_e}{2}\,C_{(ne-2)}\cos n_e\theta$$

$$-\sum_{n_e=0}^{n_e=\infty}\frac{n_e}{2}\,C_{(ne+2)}\cos n_e\theta\Bigg] \qquad \textbf{(B-49)}$$

The voltage induced in phase c may be determined in a similar manner and will be found to be equal to that induced in phase b.

The total voltage induced in phase a will be,

$$\frac{d\,\psi_a}{dt} = \frac{d\,\psi_{a1}}{dt} + \frac{d\,\psi_{a2}}{dt} \qquad \textbf{(B-50)}$$

By adding Equation (**B-11a**) to Equation (**B-44**), the following expression for the total voltage in phase a is obtained.

$$\frac{d\,\psi_a}{dt} = -\frac{(3+k_q)}{4}\sin\theta - \frac{3\,(1-k_q)}{4}\sin 3\theta$$

$$-\frac{\delta\,(1-k_q)^2}{2\,k_q}\sin(4\theta+\phi)$$

$$-\left[\frac{\delta\,(1-k_q^2)}{2\,k_q}\sin\phi + 2\sqrt{3}\,D\,C_0\right]\cos 2\theta$$

$$-2\sqrt{3}\,D\,B_2\cos 4\theta - \sqrt{3}\,D\Bigg[\sum_{n_o=-1}^{n_o=\infty}-\frac{n_o}{2}\,B_{(no+2)}\sin n_o\theta$$

$$+\sum_{n_o=3}^{n_o=\infty}\frac{n_o}{2}\,B_{(no-2)}\sin n_o\theta + \sum_{n_e=4}^{n_e=\infty}\frac{n_e}{2}\,C_{(ne-2)}\cos n_e\theta$$

$$-\sum_{n_e=0}^{n_e=\infty}\frac{n_e}{2}\,C_{(ne+2)}\cos n_e\theta\Bigg] \qquad \textbf{(B-51)}$$

The total voltage across phases a and b is the difference between the voltages represented by Equations (**B-51**) and (**B-49**):

$$\frac{d\,\psi_{ab}}{dt} = -\frac{3}{8}\,(3+k_q)\sin\theta - \frac{9}{8}\,(1-k_q)\sin 3\theta$$

$$-\frac{3}{4}\,\frac{(1-k_q)^2}{k_q}\,\delta\sin(4\theta+\phi) - \left[\frac{3}{4}\,\frac{(1-k_q^2)}{k_q}\,\delta\sin\phi\right.$$

$$\left.+3\sqrt{3}\,D\,C_0\right]\cos 2\theta - 3\sqrt{3}\,D\,B_2\cos 4\theta$$

$$+\frac{3}{2}\sqrt{3}D\left[\sum_{n_o=-1}^{n_o=\infty}\frac{n_o}{2}B_{(no+2)}\sin n_o\theta - \sum_{n_o=3}^{n_o=\infty}\frac{n_o}{2}B_{(no-2)}\sin n_o\theta - \sum_{n_e=4}^{n_e=\infty}\frac{n_e}{2}C_{(ne-2)}\cos n_e\theta + \sum_{n_e=0}^{n_e=\infty}\frac{n_e}{2}C_{(ne+2)}\cos n_e\theta\right] \tag{B-52}$$

To facilitate calculations of recovery voltage magnitudes for various values of k_q, it is convenient to convert all coefficients into functions of k_q. The terms $D\,C_0$, and the product of all coefficients by the term D may be expressed as functions of k_q. Thus the following substitutions may be made in Equation (**B-52**).

$$D\,C_0 = C_0' = -\frac{\sqrt{3}\,(1-k_q)^3\,\delta\sin\phi}{24\,k_q\,(1+k_q)} + \frac{(1-k_q)\,C_2'}{2\,(1+k_q)} \tag{B-53}$$

$$D\,B_1 = B_1' = \frac{(1+k_q) - \frac{1}{2}(1-k_q)\,(m-1)}{\sqrt{3}\left[4\left(\frac{1+k_q}{1-k_q}\right)^2 + 2\left(\frac{1+k_q}{1-k_q}\right)(1-m) - (1+m)\right]} \tag{B-54}$$

$$D\,B_2 = B_2' = -\frac{\sqrt{3}\,(1-k_q)^2\cos\phi}{12\,k_q} \tag{B-55}$$

$$D\,B_3 = B_3' = \frac{2}{\sqrt{3}\left[4\left(\frac{1+k_q}{1-k_q}\right)^2 + 2\left(\frac{1+k_q}{1-k_q}\right)(1-m) - (1+m)\right]} \tag{B-56}$$

$$D\,C_2 = C_2' = -\frac{\sqrt{3}\,\delta\sin\phi\,(1-k_q)^4\,[(1+k_q)-(1-k_q^{1/2})^2]}{12\,k_q\,[4\,(1+k_q)^3 - 2\,(1-k_q^{1/2})^2\,(1+k_q)^2 - 3\,(1-k_q)^2\,(1+k_q) + (1-k_q)^2\,(1-k_q^{1/2})^2]} \tag{B-57}$$

$$D\,C_4 = C_4' = -\frac{2\sqrt{3}\,\delta\sin\phi\,(1-k_q)}{3\left[(1+k_q) - 4\frac{(1+k_q)^3}{(1-k_q)^2} + 2\,(1+k_q) + \frac{2\,(1+k_q)^2\,(1-k_q^{1/2})^2}{(1-k_q)^2} - (1-k_q^{1/2})^2\right]} \tag{B-58}$$

By making the above substitutions the expression for the total voltage across phases a and b or a and c becomes

$$\frac{d\,\psi_{ab}}{dt} = \frac{d\,\psi_{ac}}{dt} = -\frac{3}{8}(3+k_q)\sin\theta - \frac{9}{8}(1-k_q)\sin 3\theta$$

$$-\frac{3}{4}\frac{(1-k_q)^2}{k_q}\delta\sin(4\theta+\phi) - \left[\frac{3}{4}\frac{(1-k_q^2)}{k_q}\delta\sin\phi\right.$$

$$\left.+ 3\sqrt{3}\,C_0'\right]\cos 2\theta - 3\sqrt{3}\,B'_2\cos 4\theta$$

$$+\frac{3}{2}\sqrt{3}\left[\sum_{n_o=-1}^{n_o=\infty}\frac{n_o}{2}B'_{(no+2)}\sin n_o\theta - \sum_{n_o=3}^{n_o=\infty}\frac{n_o}{2}B'_{(no-2)}\sin n_o\theta - \sum_{n_e=4}^{n_e=\infty}\frac{n_e}{2}C'_{(ne-2)}\cos n_e\theta + \sum_{n_o=0}^{n_e=\infty}\frac{n_e}{2}C'_{(ne+2)}\cos n_e\theta\right] \tag{B-59}$$

An inspection of Equation (**B-59**) reveals that the recovery voltage magnitude depends in part upon both the angle θ and the angle ϕ. Since we are interested in the values of these angles when the current in phase a is zero, the relation between θ and ϕ is obtained by equating the expression (**B-4**) to zero, and solving for the values of θ corresponding to various values of ϕ. For $k_q = 1.5, 2.0$, and 2.5, there are two values of θ for every value of ϕ considered.

Figs. 27 to 30 inclusive are families of curves of recovery voltage magnitudes plotted against the angle ϕ for various values of k_q and δ. Equation (**B-59**) was used in the solution for the recovery voltage magnitudes.

For values of k_q other than $k_q = 1.0$, and when δ does not equal zero the angle separating the two points of zero current is different from 180 deg. The slope of the current curve is different at the two zero points. Therefore, two different values of recovery voltage occur for each combination of ϕ, δ, and k_q.

When the armature transients have died away: *i. e.*, when $\delta = 0$, the two values of e are independent of ϕ and are both equal to $\frac{3}{2}k_q$, the value given in the body of the paper. For values of δ other than zero, one set of values of e is uniformly below $\frac{3}{2}k_q$. The other set of

values, however, is above $\frac{3}{2} k_q$ for values of ϕ between approximately 40 deg. and 90 deg.

Unless the breaker is timed to clear the circuit at a specific current zero, it may choose the zero associated with the lower value of recovery voltage. Thus the circuit may be more easily interrupted before the armature transients have died away than afterwards.

If the breaker is timed to interrupt at a specific current zero, however, its duty will be somewhat more severe for certain values of ϕ when the direct-current component and the even harmonics are present than after they have vanished.

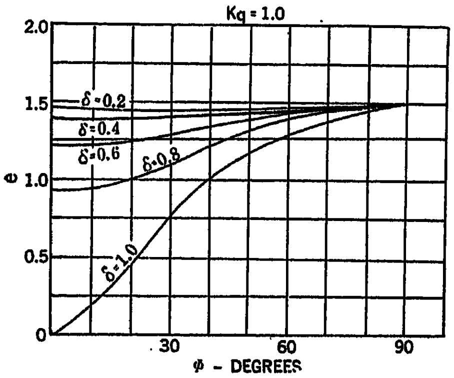

FIG. 27—VALUES OF RECOVERY VOLTAGE AS A FUNCTION OF ϕ AND δ FOR A THREE-PHASE SHORT CIRCUIT FOR WHICH $k_q = 1.0$

ϕ = Displacement angle between the phase axis and the direct axis of the rotor at the instant of short circuit

$\delta = \dfrac{\text{Per cent displacement at the time of interruption}}{\text{Per cent displacement of initial current wave}}$

Appendix C

This appendix calculates the magnitude of the recovery voltage appearing across the circuit breaker terminals of the first phase to clear of a purely reactive three-phase grounded short circuit after the d-c. component and the second harmonic have decayed to zero for a synchronous machine.

The calculation follows:

The phase opening first is designated phase a, the others being, in normal sequence, b, and c. The circuit is, therefore, that of Fig. 25.

At the time when the current in phase a is passing through zero, that phase is in line with the quadrature axis of the machine.

The negative currents arising in the three phases upon interruption of current in phase a may be set equal to $i_a' t$, $i_b' t$, and $i_c' t$ respectively for a short time following the instant of interruption, t being measured in electrical radians from the instant of interruption.

Hence, flux linkages arising from the negative current are

$$\psi_q = \frac{2}{3} x_q'' [i_a' + (i_b' + i_c') \cos 120°] t$$

$$= \frac{2}{3} x_q'' t \left(i_a' - \frac{i_b' + i_c'}{2} \right) \quad \text{(C-1)}$$

$$\psi_d = \frac{2}{3} x_d'' t [i_a' \cos 90° + i_b' \cos 30° + i_c' \cos 150°]$$

$$= \frac{1}{\sqrt{3}} x_d'' t (i_b' - i_c') \quad \text{(C-2)}$$

$$\psi_0 = \frac{x_0 t}{3} (i_a' + i_b' + i_c') \quad \text{(C-3)}$$

From these,

$$\psi_b = \psi_q \cos 120° + \psi_d \cos 30° + \psi_0$$

$$= -\frac{x_q'' t}{3} \left(i_a' - \frac{i_b' + i_c'}{2} \right) + \frac{x_d'' t}{2} (i_b' - i_c')$$

$$+ \frac{x_0 t}{3} (i_a' + i_b' + i_c') = 0 \quad \text{(C-4)}$$

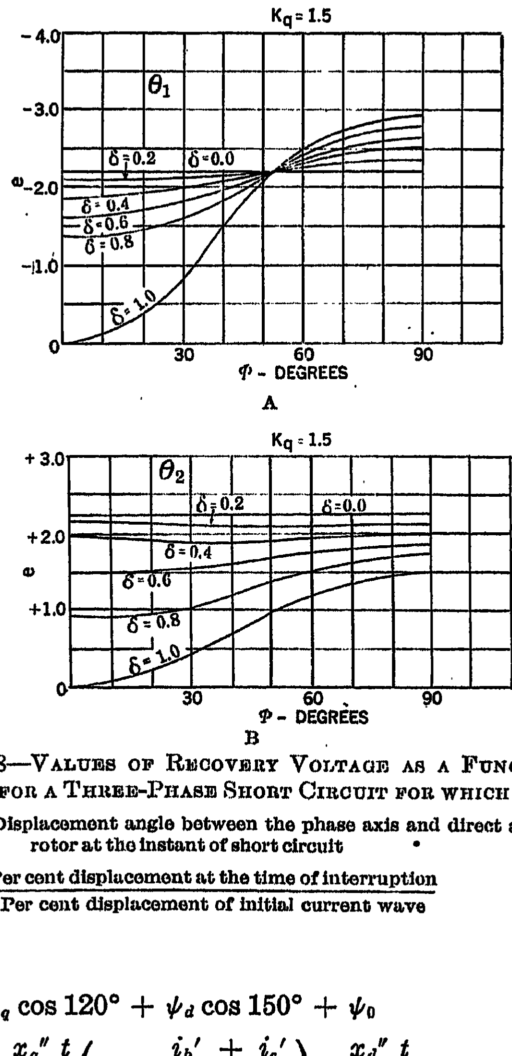

FIG. 28—VALUES OF RECOVERY VOLTAGE AS A FUNCTION OF ϕ AND δ FOR A THREE-PHASE SHORT CIRCUIT FOR WHICH $k_q = 1.5$

ϕ = Displacement angle between the phase axis and direct axis of the rotor at the instant of short circuit

$\delta = \dfrac{\text{Per cent displacement at the time of interruption}}{\text{Per cent displacement of initial current wave}}$

and,

$$\psi_c = \psi_q \cos 120° + \psi_d \cos 150° + \psi_0$$

$$= -\frac{x_q'' t}{3} \left(i_a' - \frac{i_b' + i_c'}{2} \right) - \frac{x_d'' t}{2} (i_b' - i_c')$$

$$+ \frac{x_0 t}{3} (i_a' + i_b' + i_c') = 0 \quad \text{(C-5)}$$

ψ_b and ψ_c are set equal to zero because these two phases are short-circuited and hence can build up no flux linkages. The equality holds for all values of t, hence the t may be cancelled from the third members of Equations (**C-4**) and (**C-5**). In subsequent references to these equations, therefore, t will be considered cancelled.

Subtracting (**C-5**) from (**C-4**)

$$x_d''\,(i_b' - i_c') = 0 \qquad \textbf{(C-6)}$$

whence

$$i_b' = i_c' \qquad \textbf{(C-7)}$$

Substituting (**C-7** in (**C-4**)

$$-\frac{x_q''}{3}\,(i_a' - i_b') + \frac{x_0}{3}\,(i_a' + 2\,i_b') = 0 \qquad \textbf{(C-8)}$$

$$i_a'\,(x_0 - x_q'') + i_b'\,(2\,x_0 + x_q'') = 0 \qquad \textbf{(C-9)}$$

$$i_b' = i_a'\,\frac{x_q'' - x_0}{x_q'' + 2\,x_0} \qquad \textbf{(C-10)}$$

Now

$$\psi_a = \psi_q \cos t - \psi_d \sin t + \psi_0 \qquad \textbf{(C-11)}$$

Whence, when $t = 0$,

$$e_a = \frac{d\,\psi_a}{dt} = \frac{d\,\psi_q}{dt} - \psi_d + \frac{d\,\psi_0}{dt} \qquad \textbf{(C-12)}$$

At time $t = 0$, the values of $\frac{d\,\psi_q}{dt}$ may be determined by substituting in (**C-1**) from (**C-7**) and (**C-10**) and differentiating,

ψ_d is seen from Equation (**C-2**) to be equal to zero,

and $\frac{d\,\psi_0}{dt}$ may be determined by substituting in (**C-3**) from (**C-7**) and (**C-10**) and differentiating.

Performing these operations:

$$e_a = \frac{d\,\psi_a}{dt} = \frac{2}{3}\,x_q''\,i_a'\left(1 - \frac{x_q'' - x_0}{x_q'' + 2\,x_0}\right) + \frac{x_0}{3}\,i_a'\left(1 + 2\,\frac{x_q'' - x_0}{x_q'' + 2\,x_0}\right) \qquad \textbf{(C-13)}$$

$$= i_a'\left(\frac{2\,x_q''\,x_0}{x_q'' + 2\,x_0} + \frac{x_q''\,x_0}{x_q'' + 2\,x_0}\right) = \frac{3\,i_a'\,x_q''\,x_0}{x_q'' + 2\,x_0} \qquad \textbf{(C-14)}$$

But e_a is equal to e, the circuit breaker recovery voltage, and $i_a' = k_\delta\,\frac{E}{x_d''}$, where E is the voltage existing before short circuit at the point under consideration.

Hence

$$e = k_\delta\,E\,\frac{3\,x_q''\,x_0}{x_d''\,(x_q'' + 2\,x_0)} \qquad \textbf{(C-15)}$$

This equation may be written

$$e = k_\delta \cdot k_g \cdot k_q \cdot E, \qquad \textbf{(C-16)}$$

Where

$$k_g = \frac{3\,x_0}{s_q'' + 2\,x_0} \qquad \textbf{(C-17)}$$

and

$$k_q = \frac{s_q''}{s_d''} \qquad \textbf{(C-18)}$$

The substitution of s_q'' and s_d'' for x_q'' and x_d'' respectively in Equations (**C-17**) and (**C-18**) makes these equations suitable for use at any point on a transmission system or network.

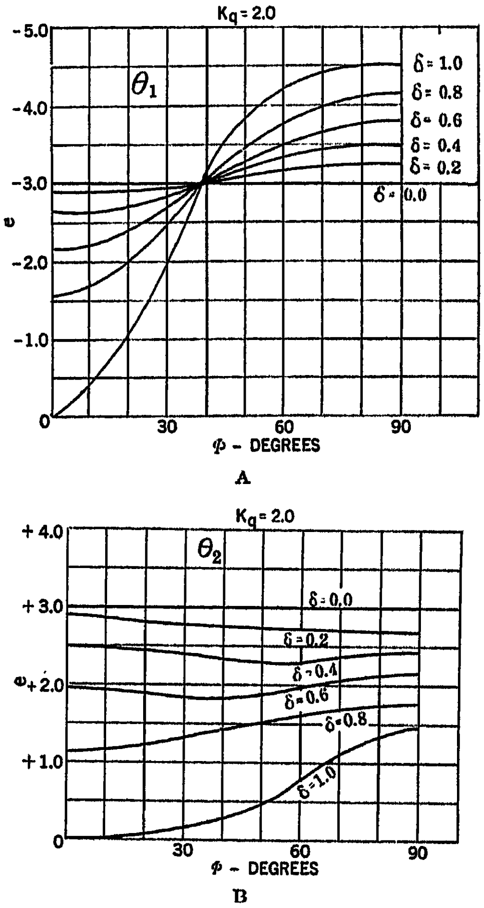

FIG. 29—VALUES OF RECOVERY VOLTAGE AS A FUNCTION OF ϕ AND δ FOR A THREE-PHASE SHORT CIRCUIT FOR WHICH $k_q = 2.0$

ϕ = Displacement angle between the phase axis and the direct axis of the rotor at the instant of short circuit

$\delta = \dfrac{\text{Per cent displacement at the time of interruption}}{\text{Per cent displacement of initial current wave}}$

The use of E as the voltage existing before short circuit neglects the effect of load current flowing previous to short circuit. The effect of load current is usually quite small, but it may be approximately taken into account by increasing the value of E in the ratio of the vector sum of load current and short-circuit current to the short-circuit current.

Appendix D

This appendix calculates the magnitude of the recovery voltage associated with the first phase to clear

of a two-phase-to-ground short circuit after the armature transients have died away.

The method of calculation is as follows:

1. The flux linkages for the two short circuited phases are set equal to zero, Park and Robertson's equations for these flux linkages being used. This gives two simultaneous equations which may be solved for the two currents.

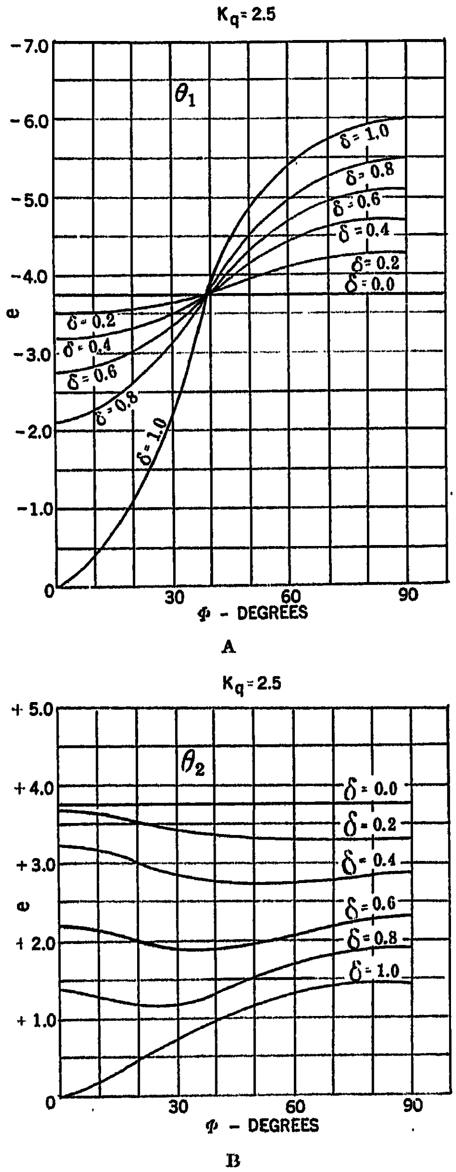

FIG. 30—VALUES OF RECOVERY VOLTAGE AS A FUNCTION OF ϕ AND δ FOR A THREE-PHASE SHORT CIRCUIT FOR WHICH $k_q = 2.5$

ϕ = Displacement angle between the phase axis and the direct axis of the rotor at the instant of short circuit

$$\delta = \frac{\text{Per cent displacement at the time of interruption}}{\text{Per cent displacement of initial current wave}}$$

2. From the current equations, the position of the rotor at the time when the current is zero is determined, and also the slope of the current wave at the zero.

3. A negative current is assumed to flow in one phase, equal and opposite to the short-circuit current there and the current induced in the other phase by this negative current is calculated by setting the flux linkages in this other phase equal to zero.

4. The flux linkages in the first phase due to the negative current in that phase and the induced current in the other phase are then calculated. The expression for flux linkages is then differentiated and values of angles are substituted for the time when the negative current is equal to zero. This gives the voltage occurring across the first phase to clear at the instant of interruption.

Park and Robertson give the following expressions for the flux linkages of phases b and c in terms of the instantaneous currents flowing in all circuits of the machine:

$$\psi_b = I_d \cos(\theta - 120°) - I_q \sin(\theta - 120°) - x_0 \frac{i_a + i_b + i_c}{3} - \frac{x_d + x_q}{3}\left(i_b - \frac{i_c + i_a}{2}\right)$$
$$- \frac{x_d - x_q}{3}\left[i_a \cos(2\theta - 120°) + i_b \cos(2\theta + 120°) + i_c \cos 2\theta\right] \quad \textbf{(D-1)}$$

$$\psi_c = I_d \cos(\theta + 120°) - I_q \sin(\theta + 120°) - x_0 \frac{i_a + i_b + i_c}{3} - \frac{x_d + x_q}{3}\left(i_c - \frac{i_a + i_b}{2}\right)$$
$$- \frac{x_d - x_q}{3}\left[i_a \cos(2\theta + 120°) + i_b \cos 2\theta + i_c \cos(2\theta - 120°)\right] \quad \textbf{(D-2)}$$

In these equations,

I_d and I_q are the field currents in the direct and quadrature axes respectively,

i_a, i_b, and i_c are the three phase currents,

x_0 is the zero phase-sequence reactance,

x_d and x_q are the machine reactances in direct and quadrature axes respectively, and θ is the angle from the axis of phase a to the direct axis at the rotor, being considered positive when the direct axis of the rotor is displaced from the axis of phase a in the direction of normal phase rotation.

Normal phase rotation is a, b, c.

In the work that follows, subtransient reactances will be used, so that it will be unnecessary to consider the current variations in the rotor.

For a two-phase-to-ground short circuit on phases b and c at normal excitation,

$$\psi_b = \psi_c = I_q = i_a = 0$$

and

$$I_d = 1.$$

Making these substitutions, Equations (**D-1**) and (**D-2**) become, respectively,

$$0 = \cos(\theta - 120°) - x_0 \frac{i_b + i_c}{3} - \frac{x_d'' + x_q''}{3}\left(i_b - \frac{i_c}{2}\right)$$
$$- \frac{x_d'' - x_q''}{3}\left[i_b \cos(2\theta + 120°) + i_c \cos 2\theta\right] \quad \textbf{(D-3)}$$

$$0 = \cos(\theta + 120°) - x_0 \frac{i_b + i_c}{3} - \frac{x_d'' + x_q''}{3}\left(i_c - \frac{i_b}{2}\right)$$

$$- \frac{x_d'' - x_q''}{3} [i_b \cos 2\theta + i_c \cos(2\theta - 120°)] \quad \text{(D-4)}$$

Adding Equations (D-3) and (D-4):

$$0 = -\cos\theta - \frac{2x_0}{3}(i_b + i_c) - \frac{x_d'' + x_q''}{6}(i_b + i_c)$$

$$+ \frac{x_d'' - x_q''}{3} [i_b \cos(2\theta - 120°) + i_c \cos(2\theta + 120°)] \quad \text{(D-5)}$$

Subtracting Equation (D-4) from Equation (D-3):

$$0 = \sqrt{3}\sin\theta - \frac{x_d'' + x_q''}{2}(i_b - i_c)$$

$$- \frac{x_d'' - x_q''}{3}[\sqrt{3}\, i_b \cos(2\theta + 150°) - \sqrt{3}\, i_c \cos(2\theta - 150°)] \quad \text{(D-6)}$$

or, $$0 = -\cos\theta - \frac{2x_0}{3}(i_b + i_c) - \frac{x_d'' + x_q''}{6}(i_b + i_c)$$

$$- \frac{x_d'' - x_q''}{6}[(i_b + i_c)\cos 2\theta - (i_b - i_c)\sqrt{3}\sin 2\theta] \quad \text{(D-7)}$$

and $$0 = \sqrt{3}\sin\theta - \frac{x_d'' + x_q''}{2}(i_b - i_c)$$

$$+ \frac{x_d'' - x_q''}{2\sqrt{3}}(i_b + i_c)\sin 2\theta + \frac{x_d'' - x_q''}{2}(i_b - i_c)\cos 2\theta \quad \text{(D-8)}$$

Segregating terms involving $(i_b + i_c)$ from those involving $(i_b - i_c)$:

$$(i_b + i_c)\left[-\frac{2x_0}{3} - \frac{x_d'' + x_q''}{6} - \frac{x_d'' - x_q''}{6}\cos 2\theta\right]$$

$$+ (i_b - i_c)\frac{x_d'' - x_q''}{2\sqrt{3}}\sin 2\theta = \cos\theta \quad \text{(D-9)}$$

$$(i_b + i_c)\left[\frac{x_d'' - x_q''}{2\sqrt{3}}\sin 2\theta\right] + (i_b - i_c)\left[-\frac{x_d'' + x_q''}{2}\right.$$

$$\left. + \frac{x_d'' - x_q''}{2}\cos 2\theta\right] = -\sqrt{3}\sin\theta \quad \text{(D-10)}$$

Solving for $(i_b + i_c)$:

$$(i_b + i_c)\left\{\left[-\frac{2x_0}{3} - \frac{x_d'' + x_q''}{6} - \frac{x_d'' - x_q''}{6}\cos 2\theta\right]\right.$$

$$\left.\left[-\frac{x_d'' + x_q''}{2} + \frac{x_d'' - x_q''}{2}\cos 2\theta\right] - \frac{(x_d'' - x_q'')^2}{12}\sin^2 2\theta\right\}$$

$$= \cos\theta\left[-\frac{x_d'' + x_q''}{2} + \frac{x_d'' - x_q''}{2}\cos 2\theta\right] + \frac{x_d'' - x_q''}{2}\sin 2\theta$$

(D-11)

Simplifying:

$$(i_b + i_c)\frac{A - B\cos 2\theta}{3} = -x_q''\cos\theta \quad \text{(D-12)}$$

where $A = x_d'' x_q'' + x_q'' x_0 + x_0 x_d''$

and $B = x_0(x_d'' - x_q'')$

and $$(i_b + i_c) = \frac{-3x_q''\cos\theta}{A - B\cos 2\theta} \quad \text{(D-13)}$$

Similarly,

$$(i_b - i_c) = \frac{\sqrt{3}(x_q'' + 2x_0)\sin\theta}{A - B\cos 2\theta} \quad \text{(D-14)}$$

Adding,

$$i_b = \frac{-3x_q''\cos\theta + \sqrt{3}(x_q'' + 2x_0)\sin\theta}{2(A - B\cos 2\theta)} \quad \text{(D-15)}$$

When $i_b = 0$,

$$\sqrt{3}(x_q'' + 2x_0)\sin\theta = 3x_q''\cos 2\theta \quad \text{(D-16)}$$

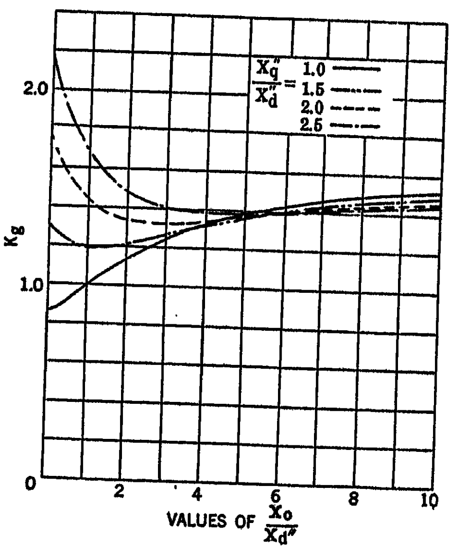

FIG. 31—VALUES OF k_g AS A FUNCTION OF $\frac{x_q''}{x_d''}$ AND $\frac{x_0}{x_d''}$ FOR A TWO-PHASE-TO-GROUND SHORT CIRCUIT

or $$\tan\theta = \frac{\sqrt{3}\, x_q''}{x_q'' + 2x_0} \quad \text{(D-17)}$$

Also,

$$\frac{d\,i_b}{d\,\theta} = \frac{3x_q''(A - B\cos 2\theta)\sin\theta + \sqrt{3}(A - B\cos 2\theta)(x_q'' + 2x_0)\cos\theta + 6Bx_q''\sin 2\theta\cos\theta - 2\sqrt{3}(x_q'' + 2x_0)B\sin 2\theta\sin\theta}{2(A - B\cos 2\theta)^2}$$

(D-18)

Substituting the following, which are obtained from (D-17),

$$3\,x_q'' = 2\sqrt{3}\sqrt{x_q''^2 + x_q''\,x_0 + x_0^2}\sin\theta \qquad \text{(D-19)}$$

$$x_q'' + 2\,x_0 = 2\sqrt{x_q''^2 + x_q''\,x_0 + x_0^2}\cos\theta \qquad \text{(D-20)}$$

we have

$$\frac{d\,i_b}{d\,\theta} = \frac{\sqrt{3}\sqrt{x_q''^2 + x_q''\,x_0 + x_0^2}}{A - B\cos 2\,\theta} \qquad \text{(D-21)}$$

To determine the current, i_c' in c induced by the negative current, i_b' in b, we set ψ_c equal to zero.

$$0 = -\frac{x_0\,(i_b' + i_c')}{3} - \frac{x_d'' + x_q''}{3}\left(i_c' - \frac{i_b'}{2}\right)$$

$$-\frac{x_d'' - x_q''}{3}\left[i_b'\cos 2\,\theta + i_c'\cos(2\,\theta - 120°)\right] \qquad \text{(D-22)}$$

or

$$i_c'\left[-x_0 - x_d'' - x_q'' - \frac{x_d'' - x_q''}{2}(-\cos 2\,\theta + \sqrt{3}\sin 2\,\theta)\right]$$

$$= i_b'\left[x_0 - \frac{x_d'' + x_q''}{2} + \frac{x_d'' - x_q''}{2}\cos 2\,\theta\right] \qquad \text{(D-23)}$$

or $i_c' =$

$$-i_b'\,\frac{x_0 - \dfrac{x_d'' + x_q''}{2} + \dfrac{x_d'' - x_q''}{2}\cos 2\,\theta}{x_0 + x_d'' + x_q'' + \dfrac{x_d'' - x_q''}{2}(-\cos 2\,\theta + \sqrt{3}\sin 2\,\theta)} \qquad \text{(D-24)}$$

Substituting Equation (D-24) in Equation (D-1)

$$\psi_b = i_b'\left[-\frac{x_0}{3}\,\frac{\dfrac{3\,(x_d'' + x_q'')}{2} + \dfrac{(x_d'' - x_q'')}{2}(-3\cos 2\,\theta + \sqrt{3}\sin 2\,\theta)}{x_0 + x_d'' + x_q'' + \dfrac{(x_d'' - x_q'')}{2}(-\cos 2\,\theta + \sqrt{3}\sin 2\,\theta)}\right.$$

$$-\frac{x_d'' + x_q''}{6}\,\frac{3\,x_0 + \dfrac{3}{2}(x_d'' + x_q'') + \sqrt{3}\,(x_d'' - x_q'')\sin 2\,\theta}{x_0 + x_d'' + x_q'' + \dfrac{x_d'' - x_q''}{2}(-\cos 2\,\theta + \sqrt{3}\sin 2\,\theta)}$$

$$+\frac{x_d'' - x_q''}{6}\,\frac{3\,x_0 + \dfrac{x_d'' - x_q''}{2}(3\cos 2\,\theta + \sqrt{3}\sin 2\,\theta)}{x_0 + x_d'' + x_q'' + \dfrac{x_d'' - x_q''}{2}(-\cos 2\,\theta + \sqrt{3}\sin 2\,\theta)}\cos 2\,\theta$$

$$\left.+\frac{x_d'' - x_q''}{2\sqrt{3}}\,\frac{x_0 + x_d'' + x_q'' + \dfrac{x_d'' - x_q''}{2}(-\cos 2\,\theta + \sqrt{3}\sin 2\,\theta)}{x_0 + x_d'' + x_q'' + \dfrac{x_d'' - x_q''}{2}(-\cos 2\,\theta + \sqrt{3}\sin 2\,\theta)}\sin 2\,\theta\right]$$

$$= -i_b'\,\frac{A - B\cos 2\,\theta}{x_0 + x_d'' + x_q'' + \dfrac{x_d'' - x_q''}{2}(-\cos 2\,\theta + \sqrt{3}\sin 2\,\theta)} \qquad \text{(D-25)}$$

But, from (D-17),

$$-\cos 2\,\theta + \sqrt{3}\sin 2\,\theta$$

$$= \frac{3\,x_q''^2 - x_q''^2 - 4\,x_q''\,x_0 - 4\,x_0^2 + 6\,x_q''^2 + 12\,x_q''\,x_0}{3\,x_q''^2 + x_q''^2 + 4\,x_q''\,x_0 + 4\,x_0^2}$$

$$= \frac{2\,x_q''^2 + 2\,x_q''\,x_0 - x_0^2}{x_q''^2 + x_q''\,x_0 + x_0^2} \qquad \text{(D-26)}$$

Substituting Equation (D-26) in Equation (D-25) and clearing of fractions in the denominator:

$$\psi_b = -i_b'\,\frac{2\,(A - B\cos 2\,\theta)\,(x_q''^2 + x_q''\,x_0 + x_0^2)}{x_d''\,(2\,x_q'' + x_0)^2 + x_0\,(2\,x_q'' + x_0)\,(x_q'' + 2\,x_0)} \qquad \text{(D-27)}$$

Differentiating, at the current zero,

$$k_g = \frac{d\,\psi_b}{d\,t}$$

$$= -\frac{d\,i_b'}{d\,t}\,\frac{2\,(A - B\cos 2\,\theta)\,(x_q''^2 + x_q''\,x_0 + x_0^2)}{x_d''\,(2\,x_q'' + x_0)^2 + x_0(2\,x_q'' + x_0)(x_q'' + 2\,x_0)}$$

(the second term of the differential is omitted, since $i_b' = 0$)

$$= \frac{d\,i_b}{d\,t}\,\frac{2\,(A - B\cos 2\,\theta)\,(x_q''^2 + x_q''\,x_0 + x_0^2)}{x_d''\,(2\,x_q'' + x_0)^2 + x_0\,(2\,x_q'' + x_0)\,(x_q'' + 2\,x_0)}$$

$$= \frac{2\sqrt{3}\,(x_q''^2 + x_q''\,x_0 + x_0^2)^{3/2}}{x_d''\,(2\,x_q'' + x_0)^2 + x_0\,(2\,x_q'' + x_0)\,(x_q'' + 2\,x_0)} \qquad \text{(D-28)}$$

Equation (D-28) may be applied to any point on a system by using the appropriate values of s_d'', s_q'', and x_0 in place of x_d'', x_q'', and x_0 respectively. The value of x_o can, of course, be adjusted to take into account the effect of neutral reactors.

Values of k_q are plotted in Fig. 29 for values of $\frac{x_q''}{x_d''}$ from 1.0 to 2.5 and for values of $\frac{x_0}{x_d''}$ from 0 to 10.

The recovery voltage of phase c, upon the assumption that that phase opens first, may be found by a process similar to that here used for phase b. It will be found to be identical with that of phase b.

Discussion

H. M. Wilcox: A similar investigation as that described has been under way for some time in the organization with which the writer is associated and it may be said that the conclusions drawn as a result of this investigation conform very closely to the conclusions reached in this paper. One or two points of variance are noted which may be worthy of discussion.

Reference is made in the paper to a series of current rupturing tests made on a standard testing circuit, in which the voltage to ground which could be interrupted by a single pair of contacts was approximately doubled by introduction of a shunt resistance of 1,000 ohms across the circuit breaker terminals. From the nature of the circuit used, it seems probable that this resistance may have been in the form of a water rheostat involving relatively large capacity to ground—large as compared with the capacity effect in the arc-drawing space of the circuit breaker. Tests in which the writer participated, using a shunt resistance of this nature, indicated that a value of 250 to 400 ohms would have secured the same result, and led to the conclusion that the introduction of additional capacity to ground was responsible for the improved performance to a far greater degree than the actual ohmic value of the resistance used. Other tests bearing out this conclusion indicated that the distribution of voltage across the two contact breaks of a single-pole oil circuit breaker could be varied over a wide range by introducing additional capacity effect on one or the other terminal, and it was found possible on these tests to throw so large a proportion of the impressed voltage across one of two contact breaks that the circuit breaker interrupted very nearly as much voltage on one break, the other being shunted with a conductor, as when both breaks were available for rupturing purposes. From statements made later in the paper, it appears that the authors themselves are fully aware of the significance of capacity to ground in the circuit and that the apparent difference of opinion is a matter only of misinterpretation of the text.

Again reference is made to a series of interrupting tests on an operating system at Wissota Station. The test circuit in this case partook largely of the nature of a laboratory circuit in that the test circuit breaker was located close to the generator, practically no transmission line being involved. The "overshooting" in voltage referred to undoubtedly accounts for the increase in duration of arcing noted on these tests as compared with a similar series of tests at Riverside station, involving 43 mi. of 110-kv. transmission line, but the authors leave the impression that these high frequency voltages were due to certain characteristics of the water-wheel generator at Wissota Station. In the lack of any parallel system to absorb oscillations, peculiarities of the generator would without doubt produce an effect on the voltage wave of the test circuit, but in the light of other data it seems logical to conclude that the capacity to ground, unquestionably present in the 43-mi. transmission line at Riverside and largely absent in the Wissota test circuit, is sufficient to account for the absence of "over-shooting" in the one case and its presence in the other. In the standard laboratory testing circuit with which the writer is familiar, fed by a 40,000-kv-a. motor-driven generator, records taken with a magnetic oscillograph show overshooting up to 125 per cent above normal frequency restored voltage. These voltage peaks rise abruptly at each current zero after the arc has reached an appreciable length and have been observed to continue for a number of cycles before final interruption. They appear to be of the nature of a high frequency voltage superimposed over the normal frequency wave and show oscillations of the order of 2,000 to 3,000 cycles, conforming very closely to the calculated natural period of a circuit of this nature. A series of short-circuit tests was made with a three-pole 15-kv. oil circuit breaker in the 250,000-kv-a. rupturing class, using this generator, and later a series of tests was made with the same circuit breaker on a large 12,000-volt cable system, over the same range of short-circuit currents. The restored voltage was substantially the same on both sets of tests but the maximum durations of arcing noted on the laboratory circuit were 40 per cent in excess of the maximum durations recorded on the field tests. In this case the variation in performance between the two series of tests was accounted for by the relatively large difference in capacity effect between the two circuits. Other statements in the paper lead to the belief that possibly the authors adhere to this conclusion also and that the apparent difference in opinion is again due to misinterpretation of the text.

From the standpoint of the circuit breaker designer, these fast-rising, overshooting voltages appearing within a few microseconds after a current zero, are of particular interest since they are of the voltages with which his circuit breaker must contend when interrupting short-circuit currents and in general are the only voltages the circuit breaker knows anything about. His design must be such that the rate of increase of dielectric strength in the arc path after a current zero will be greater than the rate of rise of impressed voltage if his circuit breaker is to function satisfactorily. It is not a matter of approaching an ideal; it is a matter of attaining that ideal or not having a circuit breaker. Various ways are open for him to secure this result. He may insert resistance across his breaker if he wishes—and sell it if he can—but, preferably, he will decide to incorporate in his design an interrupting medium which will be adequate to cope with any rate of rise of impressed voltage that may be encountered in a practical circuit. It may be said that the circuit interrupters discussed by the writer before the Institute in the last two years, were developed on a test circuit which showed voltage characteristics of the nature described in this paper and they have proven themselves adequate to interrupt such circuits satisfactorily.

D. C. Prince: The tests conducted by the Northern States Power Company called definite attention to the difference in the behavior of switches operating directly at generator terminals and connected to long lines.

An even more complete comparative test was afforded by tests made by the American Gas & Electric Co. at Philo, Ohio, between June 30th and July 6th, 1930. In these tests it was possible to connect varying lengths of transmission line to the circuit breaker under test and so determine the effect of different lengths of line. The two upper curves in Fig. 1 give the arc length in inches per break of a General Electric explosion-chamber breaker at two different values of current and over a considerable range of transmission line length. The curves are plotted in terms of calculated recovery time; that is, elapsed time from the current zero to the peak reestablishing voltage of the system. In approximate terms the recovery time is of the order of 10 microseconds per mi. of line attached. It is observed that nearly 50 per cent reduction in arc length occurs as the connected line is increased up to 150 mi., no further gain being observed after that point has been reached.

In considering the future course of development indicated by these studies and tests three courses are open·

1. Two types of oil circuit breaker should be provided; a smaller, less expensive breaker for line switching, and a larger more expensive breaker for generator switching.

2. Generating apparatus should be modified to give lower recovery voltage rates.

3. A switch should be developed which is not sensitive to changes in recovery rate within the limits likely to be encountered.

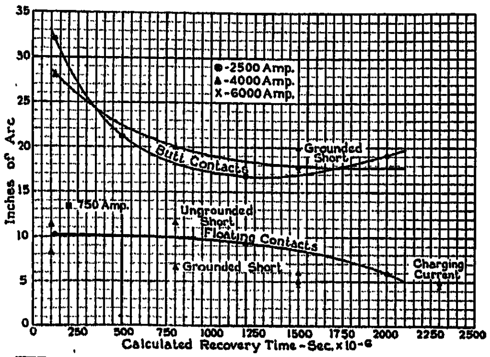

Fig. 1

Any further complexity in variety of oil circuit breakers is not likely to meet with favor. The second alternative means added expense which need not be incurred if the third alternative materializes. This third alternative seems on a fair way toward realization in the switch whose performance is recorded in the lower curve in Fig. 1.

W. F. Skeats: Mr. Wilcox in his discussion asks whether the 1,000-ohm resistor mentioned in connection with the tests described in the paper was a water box resistor and raises the question of the effect of the capacitance to ground of such a resistor. The resistor used was a combination 44 wire-wound, 90-ohm resistors arranged two in parallel and 22 in series, the entire assembly being hung in a vertical string near the breaker. It will be fairly obvious that the capacity to ground of such an assembly is very small even with respect to the capacitance of the remainder of the system.

In this connection Mr. Wilcox seems to be somewhat disturbed by the fact that some tests in which he participated indicated that a resistance of from 250 to 400 ohms would appear necessary in order to secure the results obtained from a resistance of 1,000 ohms in these tests. The comparative effect of any resistor depends probably to a very large extent upon the type of breaker upon which the tests are made and that while the data available on this point are far from complete, it is by no means the opinion of the authors that a resistance which will double the voltage at which one type of breaker will operate satisfactorily will have anything like the same result upon the performance of a breaker of any other type. Even for a given type of breaker, the comparative effect of a given ohmic value of the resistance is influenced by the voltage and current at which the breaker is operated, and also, to a very large extent, by the rate of rise obtaining before connection of the resistor. A relatively high value of resistance will be sufficient to produce a given percentage change on a very severe circuit, whereas a lower value of resistance must be used to produce the same percentage change on a milder circuit.

It would be expected that putting additional capacitance across one of the two breaks would affect the voltage distribution to such an extent that the voltage which a breaker would successfully interrupt with two breaks might be but very little greater than that which could be interrupted by a single break. It is very interesting, however, to learn that this effect has been tested and verified by Mr. Wilcox.

With reference to the tests on the Northern States Power Company system there were two factors contributing to the severity of the conditions at Wissota. One of these is the fact that the generators at Wissota are water-wheel machines, which are likely to have a much higher quadrature reactance factor than turbine-driven machines. This would increase the overshooting considerably, particularly as no other source of supply was connected to the bus and there was no external reactance. The other factor undoubtedly was, as Mr. Wilcox suggests, the large capacitance to ground present in the case of the Riverside tests but not in the Wissota tests. The capacitance to ground however does not influence the over-shoot, or magnitude of the recovery voltage peak, except to a very minor extent. What capacitance does do is to delay the rate of build-up of such voltage as does appear. The rate of voltage build-up appears to be fully as important as the magnitude of the voltage finally obtained.

Summarizing the content of the paper, the hitherto hidden phenomena of recovery voltage,—the puzzling harmonics which have sent the voltage vibrator of the oscillograph off the edge of the film and the mysterious forces which have caused the same breaker to require an arc length three times as great at one point of a system as at another point on the same system when voltage, current, and power factor were substantially the same,—are now subject to moderately precise calculation, and it can be predicted with some degree of accuracy what will be the performance at any point on any system, of any breaker whose characteristics are known.

Power Supply Facilities for Reading Suburban Electrification

BY C. L. DOUB*
Associate, A. I. E. E.

Synopsis.—The Reading Company is now electrifying its Philadelphia suburban railroad service and facilities are planned so that the electrification may readily be extended to include through passenger and freight service between Philadelphia and New York City, Bethlehem, and Reading, Pennsylvania. Contract has been made with Philadelphia Electric Company for initial power requirements, and provisions are made for enlarging such supply to serve all of the above territory.

The Railroad Company is constructing substation and transmission facilities to serve the suburban territory by a 12/24/36-kv., three-wire, single-phase, 25-cycle distribution system, with the view to serving the more remote area by superimposing 66-kv. transmission lines upon the initial system, at the time of future extension. The present and proposed system layout is described, together with the estimated power requirements and the manner in which the railroad system is to be served from the system of the power company.

THE present program of construction for electrification of Reading Company lines includes only suburban service in the vicinity of Philadelphia. This includes service to Lansdale, a distance of about 25 mi. along the Bethlehem Branch, to Langhorne, about 24 mi. along the New York Branch, to Hatboro, about 18 mi. along the New Hope Branch, to Chestnut Hill, 10.8 mi., and to Doylestown, 10 mi. from Lansdale and about 35 mi. from Reading Terminal.

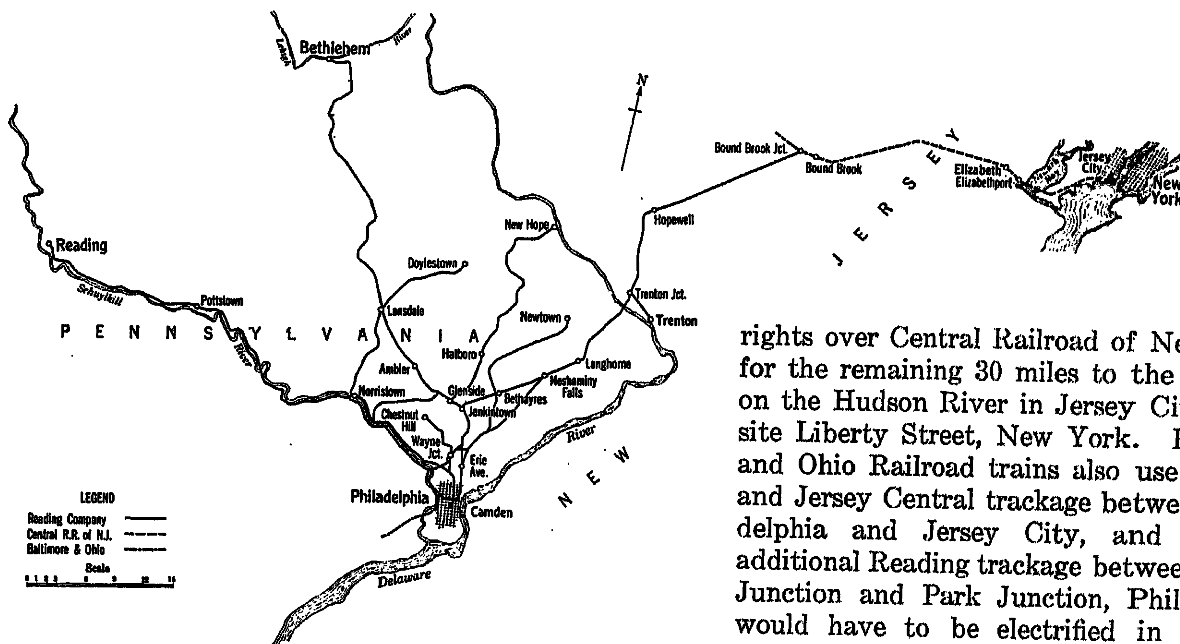

FIG. 1—PRINCIPAL READING COMPANY LINES IN TERRITORY FOR WHICH PLANS COVER POWER SUPPLY FROM PHILADELPHIA

SCOPE OF ELECTRIFICATION PLANS

All plans and designs, however, are made with the view to future extension for electric operation of through passenger and freight service. The Reading Company has announced that these plans will eventually include electrification to New York City, Bethlehem, Pa., and along the Schuylkill Valley to Reading, Pa. or beyond. Fig. 1 shows the physical arrangement of these branches. Electrification to New York involves Reading Company trackage only to Bound Brook, 60 mi. from Philadelphia, from which point this company has trackage rights over Central Railroad of New Jersey for the remaining 30 miles to the terminus on the Hudson River in Jersey City, opposite Liberty Street, New York. Baltimore and Ohio Railroad trains also use Reading and Jersey Central trackage between Philadelphia and Jersey City, and a small additional Reading trackage between Wayne Junction and Park Junction, Philadelphia, would have to be electrified in event of electrification by the Baltimore and Ohio to New York. The present suburban program includes approximately 60 route mi. and 130 mi. of track electrified, including yards, sidings, etc. An addition of the prospective through passenger electrification includes approximately 140 route miles and 380 track miles; and a further addition of freight electrification in the same area includes approximately 50 route miles and 490 track miles, making a total for all services of 250 route miles and about 1,000 track miles.

The Reading is well known as a heavy freight railroad, whose traffic density per mi. of track ranks near the top for all roads in the United States. It will be

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necessary to provide for electrification of a large number of heavy freight trains including a considerable proportion of coal trains averaging 4,200 trailing tons. The Reading passenger trains between Philadelphia and New York provide the highest type of passenger service and consistently run at speeds of 80 mi. an hr. or greater. The New York trains are of medium tonnage, carrying diners, chair cars, and club cars, but few sleeping cars on account of the relatively short distance. The Baltimore & Ohio trains using the same route include through equipment from the west and are of heavy weight. On the Bethlehem and Reading routes, the Reading provides through sleeping car service in conjunction with other railroads, and many of the passenger trains on these branches are of heavy weight.

All of the above, together with a heavy volume of Philadelphia suburban traffic and the addition of freight and passenger switching, etc., will include all forms of

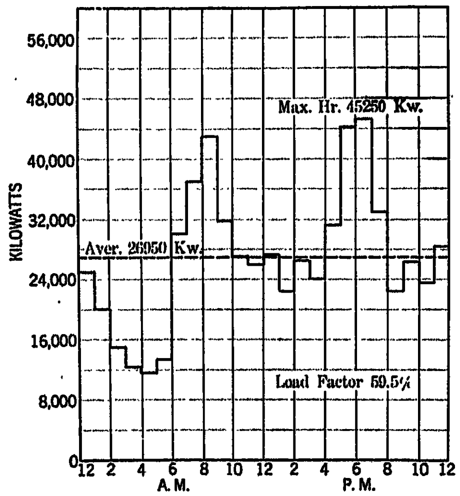

FIG. 2—ESTIMATED LOAD CURVE FOR ELECTRIFICATION BETWEEN PHILADELPHIA AND BOUND BROOK, BETHLEHEM, AND READING

Winter weekday traction load

electric railroad service, and the power system is being designed with all of these conditions in mind.

Calculations show that present loads will be about 9,000 kilowatts and 12,800 kv-a., average for maximum hr. Future loads on Reading trackage in the area which may be fed from Philadelphia will involve maximum-hr. loads of about 45,000 kilowatts and 65,000 kv-a. The load factor of the initial suburban service is typical of that of most large cities, and will be nearly 30 per cent. The addition of freight and through passenger trains, many of which are run throughout the night, raises the estimated load factor to about 60 per cent. The future load curve is shown by Fig. 2.

For the electrification of the Reading, the single-phase a-c. system was chosen, with nominally 11,000 volts on the overhead contact wires. The choice was based principally upon promoting system standardization in this territory and at the same time providing adequately for heavy freight and through passenger as well as suburban traffic. Actual design is for 12,000 volts upon the trolley.

Main Point of Power Supply. Due to the network of radiating branches from Philadelphia, it was important to choose a main point of power supply which would be convenient in serving the various lines as well as one which would be economical and readily accessible. It was early determined that in case of power being purchased, this should be at Wayne Junction, Philadelphia, which is the junction of several lines, and where the railroad had a considerable amount of property which would be available for the development of adequate system power facilities. This location is five miles from Reading Terminal, where the general offices of the company are located, together with division operating and dispatching headquarters. Negotiations with the Philadelphia Electric Company showed that this would be a convenient point of power supply for that company, being within about two miles of their Westmoreland substation, which has been developed as the Philadelphia center of the electric company's transmission and distribution system. Studies and estimates were also made on the basis of the railroad company building and operating a generating station.

The result of studies and negotiations was that the Philadelphia Electric Company would provide at Wayne Junction a 60- to 25-cycle frequency changing station to be owned and operated by that company and to supply single-phase 25-cycle power at 13,200 volts to the Reading Company at a single point. This voltage is a standard generator voltage, and must in any event be transformed by the railroad company. A contract was signed early in 1930 providing for an initial load of 9,200 kilowatts at a minimum (without penalty) of 65 per cent power factor, and 30 per cent load factor. The rates were established for initial service on the customary basis of primary or demand charge to apply to monthly maximum demand in kilowatts, and secondary or energy charge to apply to actual kilowatt hours consumed. The secondary charge is subject to correction based upon the actual cost of coal to the Philadelphia Electric Company and the actual cost of generation of hydroelectric power, properly weighed as to the proportion of steam and water power produced. The contract is for a term of 20 years, and includes provision that when the railroad company loads shall reach a predetermined value in kilowatts and load factor, which would result only from through passenger and freight electrification, charges shall be determined upon a "cost plus" basis.

The electric company determined upon a frequency changer unit of 15,000 kilowatts at 70 per cent power factor as the proper unit for installation, and two such sets will be installed in the initial station. These sets will be for outdoor installation, and will be the first of such installations in the country.

The layouts of the Philadelphia Electric and the Reading Company facilities are both made so that the Wayne Junction supply may be enlarged to a total of six such units with a capacity of 90,000 kilowatts and 128,000 kv-a. The frequency changer station will be fed by underground 13,200-volt, 60-cycle, three-phase cables from the Westmoreland Station, and duct lines with total capacity of six 18,000-kv-a. circuits are being constructed between Westmoreland and Wayne Junction, a distance of about 2 miles. Independent cables will be run for each present and future frequency changer unit, and will be fed from the duplicate 13,200-volt, 60-cycle buses at Westmoreland Station. This station is the Philadelphia terminus of the transmission lines from the recently completed Conowingo hydroelectric generating station of the Philadelphia Electric Company, and in addition to being served by lines from Conowingo (via Plymouth Meeting Substation), is also served by 66,000-volt underground transmission lines direct from Richmond and Schuylkill Stations and 13,200-volt underground lines from Delaware Station, all of which are steam generating stations of this Company in Philadelphia. The transmission lines from Conowingo, moreover, tie at Plymouth Meeting Substation into the 220-kv. ring which interconnects the power systems of the Pennsylvania Power and Light Company and the Public Service Corporation of New Jersey with that of the Philadelphia Electric Company, all of which have been described completely by Institute papers. It is thus apparent that the supply of power to the Wayne Junction Substation will be of the highest degree of reliability.

The Reading Company will construct its main substation adjacent to the frequency changer station, including transformers to step voltage up to the three-wire distribution system, and also step-up transformers for future transmission lines, together with a switching station for the trolley lines radiating from this station and headquarters for the power supervisor and load dispatchers. Cables will be run from each frequency changer set directly to generator breakers installed in the Reading Company Substation and then to the 13,200-volt 25-cycle bus provided by the Reading Company. This bus as temporarily installed will be made up of three sections, one transformer being fed from each, and the two frequency changer sets being connected to the two end sections. The bus is designed to be ultimately a six-section ring bus, each section to have one 15,000-kilowatt generator (21,400-kv-a.) and two 8,000-kv-a. step-up transformers. Adequate provisions are made for bus sectionalizing breakers together with current limiting reactors and reactor tie breakers. The bus will be installed initially as a single-phase bus, but provision is made to change this to a three-phase bus if it should be found that this is desirable for synchronizing purposes. Present calculations indicate that although motors will be paralleled through two miles of underground 13,200-volt cable, the machines will be sufficiently stable in operation that a three-phase tie will not be required on the generator sides to keep the machines in step.

Bus tie breakers will be owned and maintained by the railroad company, but will be controlled by the Philadelphia Electric Company operator. Generator breakers will be owned and operated by the electric company and transformer breakers will be owned and operated by the Reading Company. This plan is based upon the principle of the power company being responsible for maintaining an adequate supply of power on the bus, and the railroad company operator handling the power taken from the bus, considering the bus as an infallible source of supply. It will of course be necessary to arrange duplicate blocking of breakers when employees of either company work upon the bus or apparatus connected directly thereto.

Provisions for Transmission Lines. The Reading Company load calculations show that the ultimate power supply can be transmitted adequately at a voltage of 66,000 volts, and provisions are being made for the extension of two single-phase 66-kilovolt lines each in the direction of New York, Bethlehem and Reading, and southward for possible interconnection with the Baltimore and Ohio Railroad.

The physical connections between the Baltimore and Ohio, the Reading, and the Central Railroad of New Jersey make it probable that it might be desired to interconnect the electrical systems of two or more of these railroads at the time of through passenger electrification of the Baltimore and Ohio or the Reading, and the 66-kv. transmission lines will permit the interchange of a suitable block of power between these systems. This power requirement may be for normal purposes to supply the combined loads in the most reliable and economical manner, or for emergency supply when there is a deficiency of power from other normal connections. The layouts of the Philadelphia Electric frequency changer station and the railroad company main substation at Wayne Junction are both being made in such a way as to allow expansion for such purposes.

In addition to supplying power from Wayne Junction for the Reading Lines as far as Bound Brook, Bethlehem, and Reading, which cover a radius of approximately 60 miles from Philadelphia, it may be feasible to purchase power at other points near the extremities of these branches if this should prove advantageous. In this case, the 66-kv. transmission lines from Wayne Junction to such branches may or may not be run, as desired.

It will thus be seen that in the planning of the Reading Company power system for electrification, flexibility of facilities has been kept foremost so that there will be no limitations from the standpoint of power supply in the electrification of any or all of the Reading Company lines out of Philadelphia. Since the construction to Reading is not a part of the present program, there will remain further possible flexibility at the time of doing

such construction in providing arrangements for extensions beyond Reading into Central Pennsylvania, in the event it should prove desirable at that time to plan furnishing this power from Philadelphia. The distances are such, however, that it may be more economical to obtain additional power supply from some of the utilities in that territory or from a generating station located by the Reading Company itself in the mining region.

Three-Wire Distribution System. An early study of the economies and advantages of two-wire and three-wire (single-phase) transmission and distribution systems of various voltages led to the conclusion that the three-wire system having a voltage of 36 kv. between outside lines would have great flexibility for the Philadelphia area, would permit very simple and frequent substations, and would moreover be more economical in first cost and maintenance cost, even though expanded in the future by 66-kv. transmission lines paralleling the three-wire system. This system of distribution is used by the New York, New Haven and Hartford Railroad with 22 kv. between outside conductors and is used in a somewhat different arrangement by the Virginian Railway. Since the system is not altogether familiar to most engineers, the accompanying diagram (Fig. 3) will illustrate the typical connections. The trolley lines and rail connections are constructed in exactly the same manner as for the ordinary system. The operation of the third line, designated the "feeder," from the same single-phase transformer, provides a voltage between trolley and feeder of 36,000 volts which serves as a transmission line to outlying substations. There is thus a voltage of only 24 kv. between feeder and rail, and the insulation of the feeder conductors may be based upon this lower voltage.

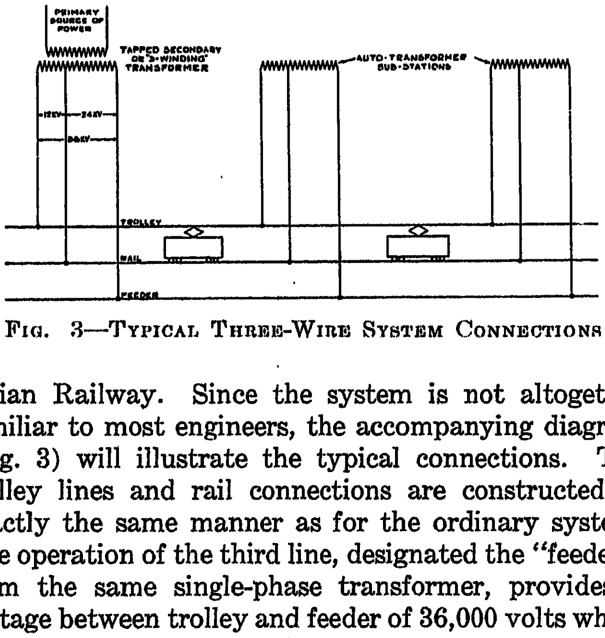

Fig. 3—Typical Three-Wire System Connections

Some advantages of the three-wire distribution system are as follows:

(a) A transmission circuit is obtained by the addition of only one wire, and this wire is at a relatively low voltage to ground, as explained above.

(b) Substation transformers are simple and economical. The step-down transformers at outlying stations are merely auto-transformers, which are relatively small in size, and connections are very simple. It may be noted that a 12/24/36-kv. 2,000-kv-a. auto-transformer is physically and electrically the same as an ordinary 12/24-kv. 1,333-kv-a. two-winding transformer when one side of the primary is connected to the proper side of the secondary. The three-wire distribution system is in principle no different from the three-wire 110/220-volt distribution commonly used for either direct current or single-phase alternating current.

(c) Substation circuit breaker and switching equipment for transmission lines and transformers are reduced in number and voltage rating, thus permitting the use of frequent substations with reasonable economy. For most railroads, switching stations are in any event required at frequent intervals for trolley lines, and these may be extended in a simple manner to include auto-transformers and feeder switching equipment. The frequent installation of transformers promotes economy in distribution similar to that which prompted the frequent installation of synchronous converter substations for direct current interurban lines after the adoption of the automatic converter station. The frequent installation of transformers also reduces the amount of current flowing in the rail and earth return circuit, and thus reduces induction in nearby circuits.

(d) Auto transformers can be designed with a lower reactance than equivalent two-winding step-down transformers, and the transmission circuit consequently be made to furnish a larger proportion of the power than otherwise.

(e) Main supply transformers, such as indicated in Fig. 3 as the tapped secondary transformer, may be designed for various proportions of reactance between primary, trolley-rail, and trolley-feeder circuits, and distribution of current may be thus regulated within certain limits. This distribution of current may then be proportioned so as to give such resultant currents in the rail and earth return circuits as to reduce inductive troubles.

(f) The feeder being a single wire, and of relatively low voltage, a certain amount of flexibility may be obtained in its location with respect to the trolley and rail circuits, so as to tend to balance inductive effects. These effects are of course dependent upon the proportion of current flowing in the three conductors of the circuit, and must be calculated for the network under consideration.

The principal disadvantages of the three-wire distribution system are that it requires more painstaking calculation than the ordinary distribution system, and that interruption of all lines in the trolley circuit also constitutes an interruption in the transmission line for all stations beyond that point, excepting such power as may be fed through the feeder and rail conductors at lower voltage than the normal trolley-feeder transmission. The latter point must be given careful consideration in the design of substations, and in the protective measures employed.

Calculations and estimates show that for the Reading

lines in the Philadelphia area the three-wire distribution system is very suitable for transmission within a radius of approximately 25 miles but that it would not be economical, and voltage regulation would not be satisfactory, for the starting of heavy trains beyond this radius. The addition of transmission lines to points beyond will therefore adequately take care of the larger territory, and this territory may be served from one or more central points through similar three-wire distribution layouts fed from stations with step-down tapped-secondary transformers. The 66-kv. transmission line would thus become a very simple line between Wayne Junction and one outlying point on each branch, requiring the higher voltage circuit breakers at only the terminal points of the transmission lines. Manual or remote-control switching apparatus for sectionalizing and cross-tying the transmission lines at intermediate points may or may not be added, as desired. The flexibility of the layout will, however, permit any or all substations along the route to be fed directly from the 66-kv. transmission lines by installing tapped-secondary transformers instead of auto-transformers, and adding the required 66-kv. switching equipment. The most important present stations are so laid out that tapped-secondary transformers may replace the auto-transformers originally installed, by making very simple changes and additions to the stations. This would occur only during some expansion of the electrification, at which time there would be need of additional auto-transformer capacity at other substations.

Circuit Breaker Protection. It was decided at an early date to use the high-speed type of circuit breaker in all trolley circuits. Very satisfactory high-speed circuit breakers had been developed for 11,000-volt trolley lines by two American electrical manufacturers, and both types of breaker had been in heavy duty service for a considerable length of time. One available type was an oil circuit breaker, and the other was an air type breaker, but both have high ratings, and both perform very heavy rupturing duty for a number of duty cycles many times that generally specified for normal speed oil circuit breakers. Both breakers demonstrated speeds of automatic tripping in from one-half to one cycle of a 25-cycle wave, and while mechanisms were radically different, results obtained were very similar. Their use decreased frequency of inspection and maintenance, minimized burning of trolley lines and equipment due to short circuits, and greatly reduced inductive effects from the railway system, but the cost of either type of available breaker was very much higher than for the corresponding normal speed circuit breaker.

The General Electric type JRA-32 air-break high-speed circuit breaker was selected for this service with a rating of 1,500 amperes continuously at 25 cycles, 15,000 volts. It has an interrupting rating (single pole) of 50,000 amperes at 12,000 volts, and is specified to perform 50 "OCO" duty cycles consecutively at two minute intervals. Its principle of tripping on the short circuits is the so-called impulse tripping, depending upon the change of 25-cycle current from one-half cycle to the next. This scheme will be essentially the same as described in a paper by Mr. J. W. McNairy, A. I. E. E. JOURNAL, October 1928. "Back-up" protection of high-speed impedance type relays is provided to take care of slowly increasing overloads and trolley-feeder faults.

Circuit breakers selected for feeder circuits are Westinghouse type GO-2, 46-kv., 800 amperes continuous rating at 25 cycles, and 500,000-kv-a. interrupting capacity (three-phase basis). They are provided with the recently developed deion grid break as described in a paper by Messrs. Baker and Wilcox presented before the Institute. Although of the so-called normal speed type, it is expected that the deion grid type of break will give speeds of interruption materially faster than ordinary oil circuit breakers. A breaker of 46-kv. rating was chosen in order to provide a sufficiently high value of insulation to compare with line insulation used on these circuits, and also to provide ability to interrupt 36-kv. trolley-feeder faults.

Breakers selected for auto-transformers and trolley-feeder side of three-winding transformers at Wayne Junction are also type GO-2 of the same rating and design throughout, excepting that they are two-pole breakers. No breaker is installed in the rail connection to these transformers, this being tied solidly to the return bus which is in turn connected directly to rails, ground wires, etc.

All of the substations constitute switching stations, and all trolley and feeder lines are sectionalized at each substation. Circuits for each track and feeder circuits in duplicate are fed separately in each direction from every substation by single-pole circuit breakers. Each section of line is therefore of the through feed type. In case of any fault from feeder to ground or trolley to ground, the single-pole circuit breakers at each end of the faulty line will operate to clear such a fault. In the event of a fault between trolley and feeder not involving ground, which will constitute a 36-kv. short circuit, relaying is so arranged as to trip breakers on both circuits involved regardless of what combination of trolley and feeder is short-circuited. Since the trolley breaker is of the high-speed type, and the feeder breaker is of the normal speed type, there would be a tendency for the lower voltage trolley breaker to operate first and attempt to clear a 36-kv. trolley-feeder fault. This action is undesirable not only from the standpoint of breaker duty but in the event the trolley breaker should successfully open the fault circuit promptly, the feeder relays might not receive sufficient impulse to trip. The energized feeder would then be left crossed with the trolley, impressing 24,000-volts-to-ground upon any apparatus such as lightning arresters, car equipment, etc., connected to this trolley.

To obviate this contingency special relay circuits

have been set up in a comparatively simple manner to prevent the trolley breaker from tripping until the feeder breaker has tripped. This is accomplished by using a current balance scheme whereby currents in feeder circuits are opposed to currents in trolley circuits, thus eliminating the impulse trip function of the trolley breaker, if the trolley and feeder fault currents are the same. The fault will operate an impedance type relay installed in the trolley circuit for back-up protection, which will not complete the high-speed breaker tripping circuit, however, until a series relay connected in the common wire to all feeder trip circuits has been energized by the tripping of the feeder breaker. In the event of a fault between trolley and feeder involving ground, this will clear as separate trolley-rail and feeder-rail faults. It may be noted that trolley-rail faults will be by far the largest number, and trolley-feeder faults not involving ground are expected to be very infrequent. For fault purposes ground and rail are considered the same, for the ground side of insulators is the steel supporting structure, which is connected directly to the rail return circuit.

Each trolley is fed at both ends, and substations are located at the terminals of all electrified branches so as to make any stub end feeds unnecessary. The elimination of such stub feeds will aid materially in obviating induction in parallel lines. Since feeders are sectionalized at each substation they are naturally connected at both ends in a manner similar to the trolley circuits.

The reliability of the railroad power facilities is further protected by differential relay protection for all transformers and for all main bus sections. Since substations are unattended, remote electrical reset is provided for trolley bus tripping relays, so that an attempt may be made to restore service on all lines immediately.

Complete transfer buses are provided for all trolley and feeder lines, so that in the event of a circuit breaker or complete bus being out of service, all outgoing lines may be energized through other breakers.

Summary

The Reading Company's initial power supply is being obtained by purchase at one point from Philadelphia Electric Company. Power is metered at 13,200 volts, 25 cycles, single-phase, and is transformed by the railroad company to serve a 12000/24000/36000 three-wire single-phase, 25-cycle distribution system. Auto-transformer substations at various points step the 36-kv. voltage down to trolley voltage.

Future electrification will be served by expanding the present facilities without change, superimposing 66-kv. transmission lines upon the present system to serve the greater distances.

It is planned to receive power May 1, 1931, for testing of lines and trains, and to begin electric suburban operation in passenger service on July 1, 1931.

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Discussion

Sidney Withington: Mr. Doub's estimate of 30 per cent load factor is of interest and is quite in line with that normally experienced in suburban service. This applies not only to the power supply but to the distribution facilities and indeed to the tracks themselves. If the electrification is extended to include passenger through service the load factor will be increased and if handling of freight is added, it will again be increased. In normal railroad operation these track facilities are available for handling freight when passenger traffic is at a minimum and there is then a desirable filling in of the valleys of the load curve if electrification covers all branches of operation. The very high density of traffic of the Reading Railroad is mentioned. It may be said to be an axiom in electric traction that density is, other things being equal, a measure of the justification of electrification.

I should like to emphasize the importance of Mr. Doub's reference to the desirability of interchangeability among railroads of electric-motive power equipment. The multiplicity of "systems" of electrification toward which we in this country are gradually drifting, will ultimately cause a great deal of embarrassment and very careful thought must in the near future be given to standardization. The railroads have necessarily gone far towards standardizing of such items as track gage, air brake facilities, car couplers, etc., and they cannot afford to be hampered in operation by the growth of a diversity of systems of power distribution in electrification. It may safely be said, I think, that standardization of this important feature will do more to stimulate railroad electrification in this country than any other one thing.

The subject of purchase of power as compared to production by the railroad is of vital importance. Power companies are now well equipped physically to supply the needs of railroads. This was not the case 20 years ago. A railroad in installing an electrification project should expect to confine its immediate capital expenditures to its power distribution facilities which at best are expensive. The motive power can usually be purchased on an equipment trust basis and paid for over a term of years from savings. The local power supply company should be the organization to make the necessary expenditures for power generation facilities. There is no fundamental reason why the railroad should not purchase power from specialists just as it purchases let us say, its castings; few railroads operate their own foundries. The power company however obviously must present to the railroad a figure for price of power which will at least not be in excess of that for which the railroad can produce its own power, and must not burden the railroad with unnecessary guarantees and limitations which would unduly penalize the railroad in maintaining the flexibility of its supply. If the railroad purchases its power requirements, the power should, if possible, be delivered to the railroad distribution system in the

form (whether direct current or single-phase) in which it is to be used, that is, under normal conditions the power company should own and operate any substations facilities which may be necessary as part of the supply.

The reliability of railroad operation depends upon duplication of facilities. Railroads like many other public service organizations, must operate continuously 24 hours a day throughout the year, with no time out. In winter, blizzards and sleet, in summer, lightning and at any time of the year storms may be encountered; any unit of equipment may fail in service, and maintainers or material for repairs may be far away. Duplication of important items, that is the availability of an independent facility, is the only means of assuring continuity of operation. For this reason a power company's supply with its transmission network independent of railroad right-of-way may be ideal. A wreck or a fire on property adjacent to the right-of-way may cut the railroad in two and an independent supply is thus essential to continued operation. In the case of the Reading electrification this is not an essential consideration for its network of tracks provides opportunity for ring feeders of its own.

Mr. Doub refers to high-speed circuit breakers. Such protective facilities, designed to quickly clear any fault which may occur has done a great deal to advance the art of electric operation of railroads, whether on single-phase or d-c. distribution systems. From the very nature of the kind of operation, frequent grounds and short circuits are experienced in railroad power supply circuits and these on the grounded systems are often very severe. Quick clearing of the fault is essential to protect the equipment as well as to minimize transfer of induced power to neighboring communication facilities. The high capacity high-speed circuit breakers, whether air or oil, accomplish this very satisfactorily and simplify operation.

Substations of the Broad Street Subway of Philadelphia

BY H. M. VAN GELDER[1]
Member, A. I. E. E.

Synopsis.—*The Broad Street subway is the first step of a system of underground high-speed railways which is being designed and built by the City of Philadelphia. This paper describes the substations which furnish power for traction at 630 volts direct current and for the subway lighting and signals at 4,600 volts, 60 cycles.*

The first section of the Broad Street subway required three substations which were equipped with synchronous converters and completed in 1928. Later, when the subway was extended, a fourth substation was added, but by this time so much progress had been made in the design of substation apparatus, particularly in respect to increasing the current capacity of mercury arc rectifiers and perfecting iron-clad high-voltage switching equipment, that a radically new design of substation was decided upon embodying these types of apparatus. This substation was placed in operation this year.

This paper contains a description of the apparatus and method of operation provided in both types of substations and indicates the advantages of the equipment selected. Much thought was also given to special operating features for safety and reliability.

* * * * *

INTRODUCTION

THE construction of the Broad Street subway was started in 1924, the first section extending from City Hall to Olney Avenue, approximately six miles, with a half mile extension to the Fern Rock Yard. It was built for four tracks but only the two local tracks were installed. This section was placed in operation in 1928.

Early in the construction when clearances of the tunnel were determined it was decided to install a traction system using contact rail distribution at a potential of 600 volts direct current. Power was available from a public utility system at 13,800 volts, 60 cycles, three-phase, by underground transmission.

To supply traction power for this line and the yard three substations were constructed, spaced about two miles apart, at Louden, Cumberland, and Mt. Vernon Streets. They were built to contain sufficient equipment for the ultimate train operation on four tracks, but the initial installation was only for estimated 1930 traffic on the local tracks. The three substations are similar in design and equipment except for minor modifications to conform to the shape of the building sites.

SYNCHRONOUS CONVERTER SUBSTATIONS

The substation sites were selected just off Broad Street, generally in a fairly good residential district. As rotating apparatus was to be installed in these stations, considerable thought was given to the elimination of noise so as not to disturb the neighborhood. The buildings were constructed without windows and with walls having an inside brick veneer separated from the main wall by an air space. The main entrances were constructed with two sets of double doors having an air space between. The buildings were located on corners and an areaway or space was left on the sides adjacent to other buildings. This construction has proved very satisfactory, as almost no sound is transmitted outside of the station that can be heard across the street.

With the stations designed to be enclosed as described, it became necessary to give particular attention to the ventilation of the buildings, as all equipment was to be air cooled and no forced draft used. Liberal openings, fitted with louvers, were therefore provided in opposite sides of the basement. These openings

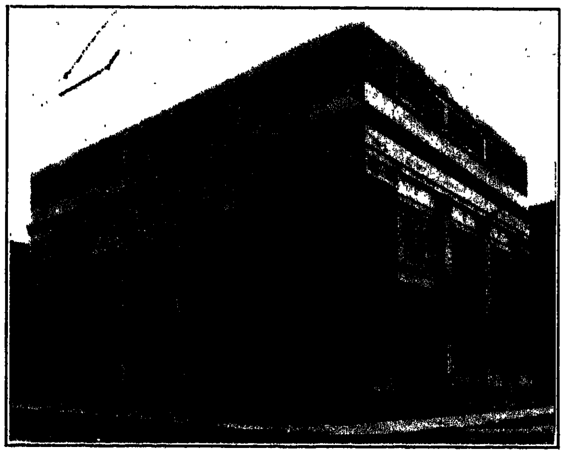

FIG. 1—LOUDEN SUBSTATION

admit air from areaways in the side walk or between buildings. Large, specially designed, stationary ventilators were located in the roof over the converters and transformers and a division wall was constructed across the center of the basement separating the converter and transformer space. Openings with gratings were located in the main floor opposite the shaft ends of the converter, as it was known that the opening through the bed plate of the converter was not satisfactory for ventilation. It will be seen that with this arrangement of air inlets in the basement and ventilators in the roof, augmented by a stack effect of about 40 ft. between the basement and roof, a real system of natural ventilation

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was established. Architectural treatment for this type of building is well shown in Fig. 1, which is a corner view of the Louden Substation.

The requirements for the ventilation system were calculated, based upon the heat units to be dissipated at 150 per cent rating of the equipment with an assumed temperature gradient, taking into account the stack effect, but without adding the ventilating capacity that would be obtained due to any outside wind velocity. The inlet and outlet openings were sized to conform to these calculated requirements. The experience and results obtained by the 1925 and 1926 Committees on Power Generation and Conversion of the A. E. R. E. A. were made use of in planning the ventilation.

The capacity of the substations was determined from proposed schedules for initial and ultimate operation of trains on the two local tracks installed, and on two additional express tracks to be installed at a later date. Motor-generator sets, synchronous converters, and mercury arc rectifiers were considered in the studies for these substations. Rectifiers had not then been in service in large capacity units, and converters showed better economy and were lower in first cost than motor-generator sets, therefore converters were chosen. They were specified to be compound wound to give better regulation of the voltage in the subway as no feeder cables are used in parallel with the 150-lb. contact rail.

The assumed traffic of the Broad Street subway showed a decided peak during morning and evening rush hours, lasting in each instance about one hour, with momentary loads during acceleration of much greater value, so that the problem of supplying the power for the traction load resolved itself into a question of maximum ratings. It was found that the continuous rating of the converter was of little importance and that the two hour rating would probably not be reached for some time in the future, hence the peak loads during acceleration of four and six car trains determined the capacity of unit required. By installing a converter unit having sufficient capacity for the initial service it required three units for ultimate operation with four tracks. Provision was made in the substation for a fourth unit to be used as a spare. Therefore, two units were installed in each substation to take care of the initial load on two tracks and to provide a spare unit.

At the time these converters were installed they were the largest 60-cycle converters built for 630-volt traction loads. They are 360 rev. per min. and compound wound with slightly drooping characteristic. The actual ratings are 3,000 kw. at 630 volts continuously, when supplied with six-phase, 60-cycle, a-c. power at 100 per cent power factor; 4,500 kw. at 630 volts for two hours; and 8,000 kw. at 560 volts for three minutes.

Oil-insulated self-cooled transformers were installed in cells at the basement floor level. In order to guard against overheating for short periods of heavy load in excessively hot weather, when ventilation might be imperfect, a water coil was installed in the transformers to provide partial cooling equivalent to the radiation required for the transformer to carry 50 per cent of its nominal rating. The transformers have auxiliary expansion tanks to prevent oxidation of the oil.

Conventional types of brick masonry structure for the 13,800-volt bus and of concrete cells for the oil circuit breakers were installed on the main floor, or in a small balcony along the side of the building. Fig. 2 is a view of the main floor of Cumberland substation showing converters and transformer cells.

The control and instrument switchboard from which all circuits are operated is located on the main floor. The main positive and equalizer leads from the converters drop directly to the main converter switchboards located in the basement. From these switchboards the 630-volt main positive circuits run directly to the positive bus, thence through the high-speed circuit breakers to the feeder switchboard and out through the underground cables and conduits to the air circuit breakers and contact rail in the subway. The main

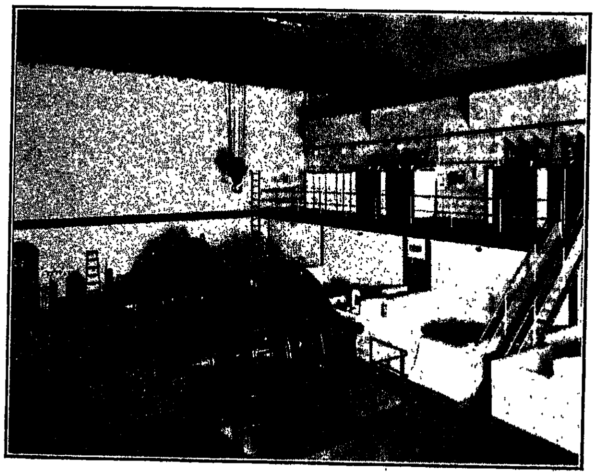

FIG. 2—MAIN FLOOR, CUMBERLAND SUBSTATION

negative leads from the converter run directly to the negative bus. Thus it will be seen that no 630-volt power circuits are brought up to the main floor, and furthermore all of these circuits are run in the basement by means of copper bars, no cable being used until the underground cables are reached. Fig. 3 is a cross section of Louden substation and shows the location of apparatus and arrangement of ventilation.

The starting and control system for the converters, has some unique features which deserve a detailed description. It was designed for star-delta starting by the automatic switching of the high-voltage windings of the transformers; for assuring correct polarity; to avoid error in brush position; and to prevent closing a dead machine onto the bus. The sequence of operations when starting the converter is as follows: The field has to be excited from the control battery circuit, to insure correct polarity, before the main oil circuit breaker can be closed by the control switch. The closing of the oil circuit breaker completes the closing circuit of the star

oil switch, provided the brushes on the converter are raised. When the converter has attained synchronous speed a relay bridges a gap in the tripping circuit of the star oil switch, and this circuit is completed by another relay which closes at a definite value of the field current after the field switch has been thrown over to self-excitation. The star oil switch on opening completes the closing circuit of the delta oil switch, provided the oil circuit breaker continues closed. The oil circuit

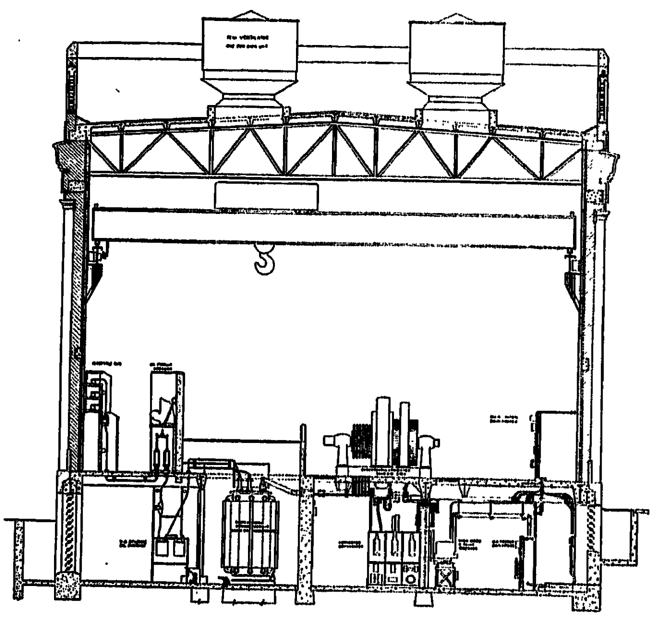

FIG. 3—CROSS-SECTION, LOUDEN SUBSTATION

breaker is trip free during the above operations so that full protection is assured. The d-c. switches and circuit breakers are electrically operated, but before the positive switch can be closed the delta oil switch must be closed, brushes lowered, equalizer switch closed, and positive circuit breaker closed.

The oil circuit breaker will open on over-current or low voltage, and, by interlock control, automatically opens either the star or delta oil switch and the d-c. circuit breaker. The d-c. breaker opens on over-current, reverse current, over-speed, or undervoltage, and on opening, opens the positive switch and the equalizer switch.

A ground relay opens both the oil circuit breaker and the d-c. breaker on a converter flash-over. Thus it will be seen that many of the operations are automatic, the operator performing only the initial movement of a sequence. The design also assures speed of operating and prevents an operator from making mistakes in putting a converter on the line. At the time of an unexpected failure of the power supply to a substation, the operator cleared all feeder circuits and auxiliaries, ordered power on again, started up the station, and established full d-c. feeder service in three minutes.

Two of the substations contain transformer and switching equipment for the supply of 4,600-volt, three-phase and single-phase power for lighting and signal feeders, respectively.

These three substations have been in operation for over two years and all equipment has functioned very satisfactorily. The converters have flashed over occasionally but have not averaged more than two or three per year per machine, and when they do occur the damage is slight and usually the machine does not have to be left out of service. The flash-overs generally occur at times when a heavy load is suddenly cut off, particularly where a limited short circuit occurs which does not open the high-speed breaker but clears itself or is cleared by a subway air circuit breaker. Apparently the flash-overs are due to large synchronizing currents caused by angular displacement of the armature after heavy momentary load.

One operator and a helper are on duty in each station at all times.

MERCURY ARC RECTIFIER SUBSTATION

When the Broad Street subway was extended south from City Hall to South Street, a distance of about three-quarters of a mile, it was necessary to build a fourth substation to furnish traction power. The site of this substation, known as No. 7 and shown in Fig. 4, is just east of Broad Street and south of Pine Street, near the southern terminus of the subway extension. The site is 80 by 80 ft., and permitted the erection of a substation having access from both Juniper and Watts Streets.

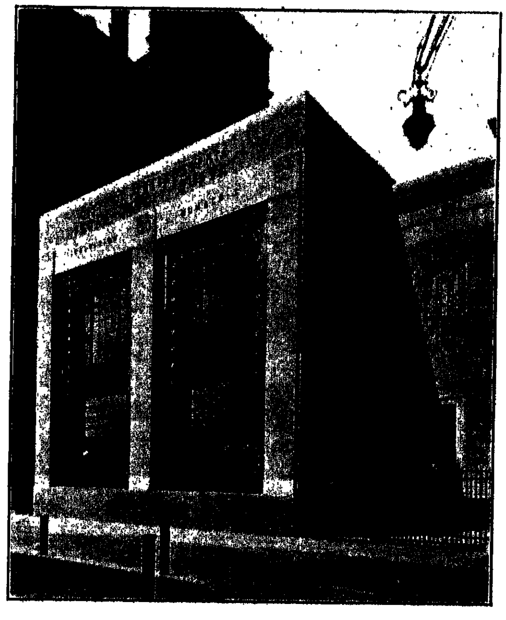

FIG. 4—SUBSTATION NO. 7

The design of substation No. 7 and its equipment was undertaken in 1929, by which time considerable experience had been obtained with the actual load and operating conditions existing in the three synchronous converter substations originally built for the Broad Street subway.

Some difficulty had been experienced with the synchronous converters flashing over under extreme load

variations, but this was not serious enough to warrant a change in the type of apparatus for this cause alone.

In the meantime much progress had been made in the design, and considerable experience gained in the operation of large capacity mercury arc rectifiers in this country. Two important companies were prepared to manufacture units for subway operation having maximum capacities of 12,000 to 15,000 amperes. Rectifiers also have many advantages over converters, such as much better efficiencies at light loads, the absence of large rotating parts with their attendant troubles and noise, the absence of commutation of heavy currents, better stability under short circuits, and the simplicity of bringing them on the line. Therefore it was decided to install rectifiers in this new substation.

Experience obtained on North Broad Street indicated that short peak loads would determine the capacity of the unit, and that these peaks usually lasted less than ten seconds or during the multiple motor operation on notching acceleration. Consequently the maximum rating of 300 per cent load was reduced from three minutes to one minute. A unit having a continuous rating of 4,000 amperes at 630 volts, 6,000 amperes at 612 volts for two hours, and 12,000 amperes at 550 volts for one minute was decided upon. As one of these units would carry the initial load, the first installation required two units, the second unit being installed as a spare. The building however was constructed to contain a total of four units which will provide for subway extensions adjacent to this substation.

Regulation of these rectifiers closely approximates that of the synchronous converters in the original substations, thus making it possible for the two types of substation to be operated in parallel even on the extreme fluctuations of load. There will be no necessity, and it is not intended, to install converters and rectifiers in the same substation for parallel operation.

Although cell structures built up of some form of masonry or steel have become fairly well standardized for high-voltage oil circuit breaker and bus equipment, live parts being more or less protected with barriers, doors, or covers, they have never proved entirely satisfactory from the standpoint of safety. Any accident or failure which occurs in such structure is sure to be serious from the standpoint of human life or interruption of service or both. There had been in use abroad and under development in this country for sometime a wholly enclosed and filled structure for bus and oil circuit breaker connections, known generally as the iron clad type of switchgear, which presented very attractive safety features. It was decided to use such equipment in the new substation.

The incoming 13,800-volt circuits, bus, oil circuit breakers, instrument transformers, disconnecting devices, and connections for this substation are all contained in an armor clad bus and switchgear structure which leaves no live part exposed. The structure is filled with hard compound, except the circuit breakers and potential transformers which are filled with oil, and the current transformers which are enclosed in a chamber filled with petrolatum. All cable leads to and from the armor clad structures are lead covered and wiped permanently to potheads which form a part of the structure. One feature of this structure is that all relays and connections are self-contained and mounted on the various switchgear units. Each armor clad structure is completely built and assembled in the factory, and no masonry structure is required in the station except for foundations. Consequently the field erection is comparatively simple. The main 13,800-volt, three-phase bus and circuit breakers are shown in Fig. 5.

The rectifiers are water cooled and the transformers are self-cooled, so that in the layout of the station building, which is located between two streets and with an areaway on each side, a central rectifier hall was provided and a separate transformer cell located in each

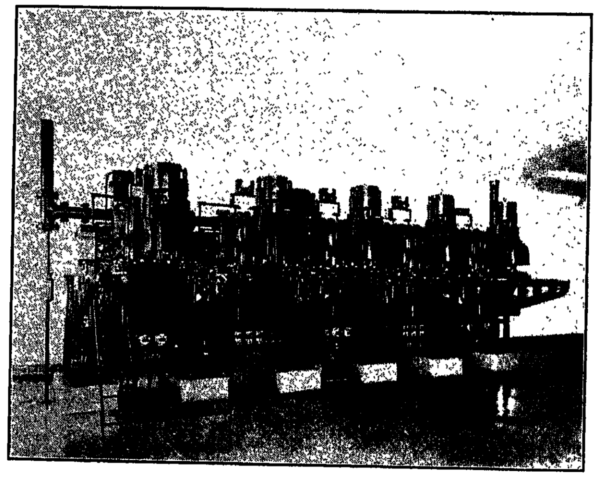

FIG. 5—MAIN 13,800-VOLT BUS AND OIL CIRCUIT BREAKERS, SUBSTATION NO. 7

of the four corners of the building. By this arrangement each transformer cell has an opening on two sides and a large roof ventilator at the top. One of these openings contains adjustable louvers and the other has a vertical lift door giving entrance from the street. This provides natural ventilation from two directions.

As there is practically no noise from the equipment of this substation no special precautions had to be observed regarding sound-proofing and no special ventilating problems were encountered except in the transformer cells as described.

The rectifiers are double six-phase, contain 12 anodes, and have automatic a-c. ignition and excitation, automatic water control, and an indicating vacuum regulator which cuts the rotary pump in and out at predetermined vacuum points, and also cuts the rectifier out of service if the vacuum falls below a predetermined value. Thermometers with electrical contacts also provide thermal protection for the rectifiers. The installation of rectifiers and their auxiliaries is shown in Fig. 6.

The water for cooling the rectifiers is taken from two city mains, two sources of supply being used to insure continuity. Due to the relatively light continuous loads and the prevailing low cost of water, it was found to be cheaper to waste the water than to provide cooling equipment for recirculating it.

Each rectifier has a static mercury vacuum pump and two rotary oil vacuum pumps, one of which is a spare. This spare pump was specified as an extra precaution against failure of the one piece of rotating apparatus included in the unit. It has been found that the rotary pump does not operate more than 25 per cent of the time.

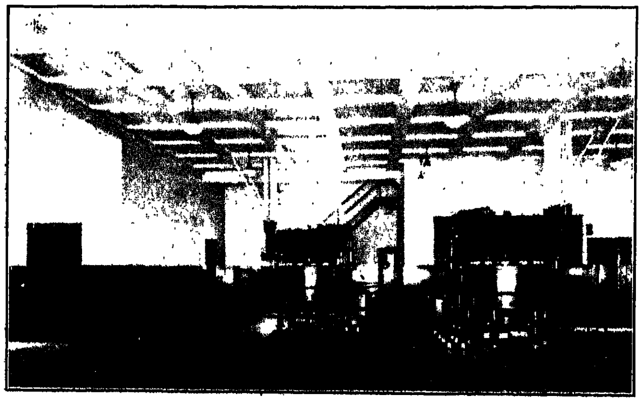

Fig. 6—Main Floor, Substation No. 7

The subway d-c. power load, a graphic chart of which is shown in Fig. 7, is of such a fluctuating character and has such a low sustained value that it was found of little use in forming or baking out the rectifier. In order to furnish a continuous load for this purpose a water rheostat which will absorb 1,200 amperes has been installed in one of the areaways outside the substation. This rheostat may be operated in parallel with the traction load. If necessary the rectifier can be operated six-phase or three-phase at times of bake-out, thus increasing the current per anode.

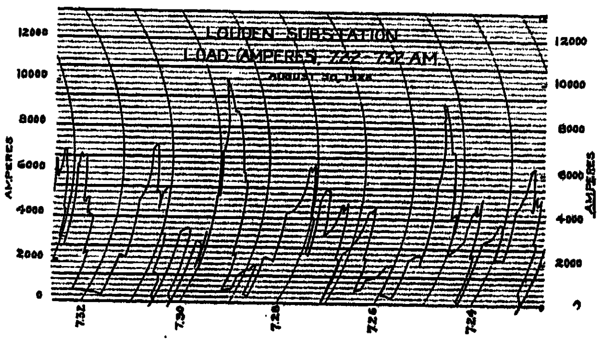

Fig. 7—Typical Substation Load of Broad Street Subway

An operating office was provided in the substation on the same floor as the rectifier hall. One side of this office consists of the main control switchboard from which all apparatus in the substation is operated and controlled. All other switchboards and all 630-volt d-c. circuits are located in the basement, following the same general design as for the converter substations, except that a single rectifier switchboard was used instead of separate converter panels under each machine as in the other substations.

The d-c. connections from the cathode of the rectifier pass directly through the floor to the rectifier switchboard. This board contains a remote-controlled positive switch and a special quick-acting circuit breaker for each rectifier, with auxiliary switches and interlocks, so that when the 13,800-volt oil circuit breaker of the rectifier unit is closed, all other functions of starting up are performed automatically; the operator has then only to close the positive d-c. circuit breaker control switch to bring the rectifier on the bus.

The four neutral connections of each main transformer are carried to the basement through wall ducts to its interphase transformer located immediately adjacent to the negative bus. The neutral lead of this interphase transformer, which forms the negative connection of the rectifier unit, is connected to the negative bus.

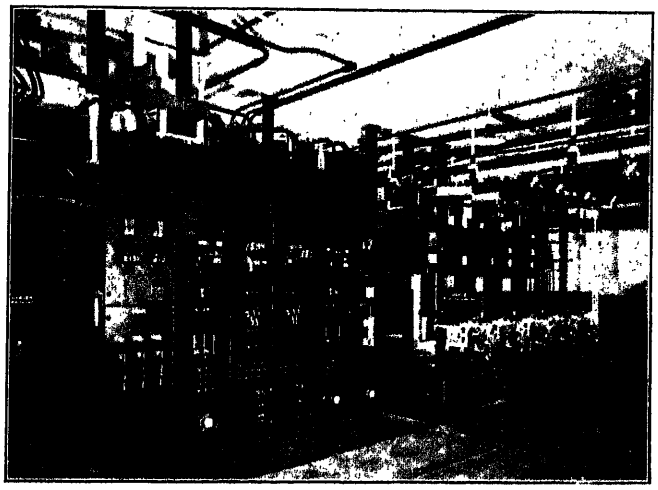

Fig. 8—Rectifier Switchboard and High-Speed Breakers, Substation No. 7

The layout of the 630-volt d-c. buses, high-speed circuit breakers, feeder switchboard, and outgoing positive feeder cables is the same as in the other substations. Fig. 8 shows the rectifier switchboard and high-speed circuit breakers.

This substation also has the station auxiliary switchboard in the basement with the principal operating circuits controlled from the main control board. The control circuits of the substation are supplied from a 125-volt storage battery. The auxiliary a-c. circuits for the rectifier units have three sources of supply to insure continuity of service: an auxiliary station transformer supplied from the 13,800-volt main bus, and a second auxiliary transformer supplied from either

of two 4600-volt lighting feeders entering the substation from the subway and supplied from different substations of North Broad Street.

There has been no signal or telephone interference experienced due to the operation of this substation. Telephone circuits in this district are carried in underground cables.

This substation was placed in regular operation April 20, 1930, and up to the present time the equipment has functioned quite satisfactorily. During early operation a few back-fires occurred, doubtless due to insufficient baking-out of the rectifier before heavy overloads were carried. However, no damage was done, and now loads of 10,000 amperes are taken by one rectifier.

Discussion

Sidney Withington: One of the striking points touched upon by Mr. Van Gelder is his reference to the fact that the mercury arc rectifier supplanted the rotary converter in his more recent substation design. The development of the rectifier for traction purposes has recently been relatively rapid. This rapid development has been indicated especially in the electrification of the Cleveland Union Terminals and D. L. & W. Hoboken suburban electrification. These two projects both employing 3,000 volts direct current for distribution were inaugurated within a short time of one another. The Cleveland Terminal design is based upon motor-generators and the D. L. & W. upon mercury arc rectifiers. The few weeks intervening mark developments of vital consequence in the use of the static rectifier for 3,000-volt service in this country.

The growing use of the mercury arc rectifier for railroad work is making increasingly desirable a logical method of rating which will recognize the fundamental thermal and other load characteristics of the rectifier as compared with rotating apparatus. Mr. Van Gelder's load curve shows clearly the disadvantages of the present standard method of rating. It is to be hoped the work of standardizing the rating which has been undertaken by the Institute under the auspices of the American Standards Association will shortly be completed so that it may be adopted by manufacturers and railroads.

H. M. Van Gelder: Our units all have a 300 per cent rating for one or three minutes, given in detail in the paper. This is essential for the peak loads carried by these substations, and is the only rating which limits the use of the equipment, the continuous and 2-hr. rating not yet having been reached. With reference to a standard rating for this type of railway equipment it does not seem practicable to me to use the same standard for different classes of load. Where small train units are operated at frequent intervals, resulting in a fairly steady base load, a maximum rating of 200 per cent might be sufficient. On the other hand, with a 2-track high-speed line moving heavy train units at longer intervals, the only rating required would be a maximum rating of 300 per cent, or even more in some cases.

Utilization of Railroad Rights-of-Way
For Electric Power Transmission and Coordination with Railroad Electrification

W. W. WOODRUFF[1] and G. I. WRIGHT[2]

Associate, A. I. E. E. Member, A. I. E. E.

ON account of a combination of factors, Philadelphia has been obliged to take several steps in the matter of utilizing railroad rights-of-way for electric power transmission purposes and has probably made a further advance along these lines than any other city in this country.

While the same factors and their relative importance may not be operative in other localities, it is probable that in the immediate vicinity of any of the larger cities, there are, or will be in existence, a combination of circumstances which would make the utilization of railroad rights-of-way for electric power transmission purposes both expedient and essential.

It is felt that the results obtained in Philadelphia have been highly satisfactory and beneficial to both the railways and electrical industry and that wider knowledge as to the general features should be of interest to others.

In order to make the situation clear, it will be well to review the various factors involved and to briefly trace through several stages of the developments.

Philadelphia is located on a peninsula formed by the junctions of the Schuylkill and the Delaware Rivers. To the south of the Schuylkill River there is an industrial development which extends through the City of Chester and Marcus Hook to the State of Delaware. West of the Delaware River there is a section of congested urban development from one to six miles deep extending for about twenty miles along the water front. Back of this strip is an area of suburban and semi-rural development which forms a belt probably some twenty miles deep and extending from the vicinity of Trenton to the Mason-Dixon Line. (Fig. 1).

The main steam plants of the Philadelphia Electric Company that supply this region with electrical energy are necessarily located along the Delaware River. A glance at a map of the territory would indicate that plants located along the Schuylkill would be in a better strategical location for feeding the territory. Locations on this river, for large stations, are however impractical on account of the fact that the river flow is comparatively small. While the oldest station of the Philadelphia Electric Company is located on the Schuylkill and is still in operation, it has not been advisable to add to its generating capacity for a number of years and it is doubtful if it will ever be expedient to rebuild or increase its capacity. Consequently, a major transmission problem has been to find means of carrying power into Schuylkill Station, to establish other points of large capacity supply at strategic locations, and to tie these up with the larger generating stations in the territory and with outside sources of supply.

When we come to considering the transmission of large blocks of power into these urban centers, from outside sources, it is generally the case that the securing

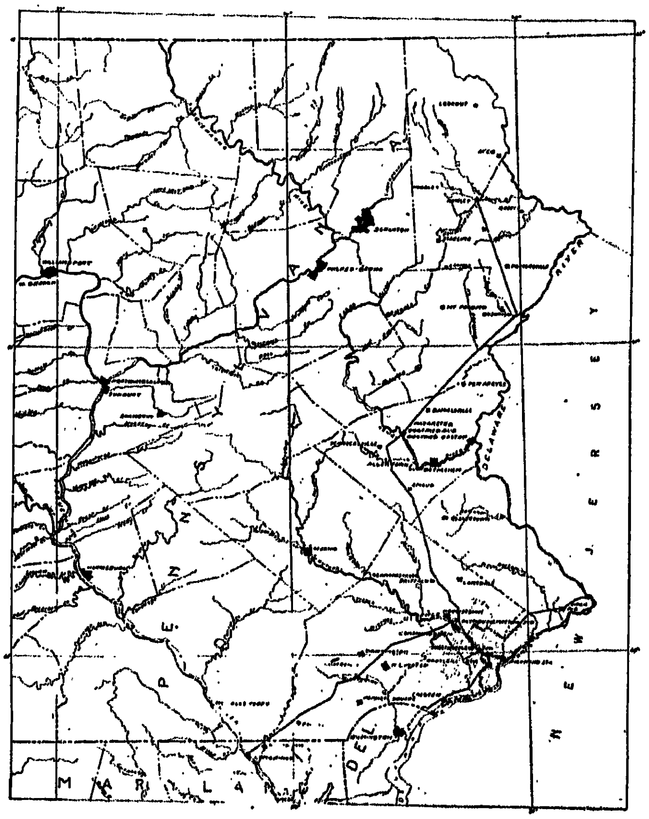

Fig. 1—Map of Territory

of satisfactory right-of-way to the economic centers of distribution is almost an impossibility and that the various railroad lines form the only feasible routes through the highly developed districts. In practically all cases the railroads own these rights-of-way.

The first major problem of this kind in Philadelphia originated about 1915-16, when it became essential for the electric company to have a 66-kv. transmission line between Schuylkill Station in Philadelphia and the new Waterside Station in Chester in order to back up

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the older station, supply more power and take advantage of the more economical generation at the newer station.

The only feasible route between these two stations was along a freight line of the Reading Railroad and a short section of the Pennsylvania Railroad which ran between Philadelphia and Chester. Practically all the property on either side of this railroad route was either developed or had so much potential value for future manufacturing sites that its purchase for transmission line purposes, or the securing of a permanent right-of-way over it, was out of the question.

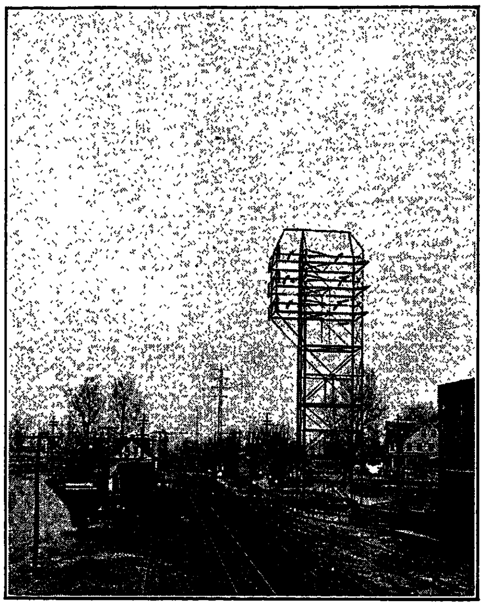

Fig. 2—66-Kv. Line Erected Along Side of Railroad Right-of-Way in 1915-16

Consequently, the transmission line was built largely on the side of the railroad right-of-way. (Fig. 2). The type of agreement between the companies was such as would naturally have been expected in that period when there was considerable difference of opinion between the railroads and the power companies about wire crossings, Pennsylvania General Order No. 13 and other items. In short, while the agreement indicated that both parties were satisfied with the arrangement, both agreed to and granted, as little as possible. Naturally the agreements had a revocation clause, as was then customary.

Practically this solution has worked out satisfactorily but this is primarily because of a disposition on the part of the companies to consider the matter in a wholly cooperative spirit rather than on account of the nature of the agreement and its legal provisions.

A similar situation developed in 1924 in connection with a project of the electric company's for interconnection between Philadelphia and Trenton. In this case the district immediately adjacent to the Richmond Station, from which circuits must run, was so highly developed that the only expedient was the running of underground cable for a distance of about four miles and thence it was possible to construct a 66-kv. steel tower transmission line on the Oxford Branch of the Pennsylvania Railroad for a distance of about five miles.

The electric company was rather loath to invest several hundred thousand dollars on a right-of-way where it had no really permanent and irrevocable rights. At the same time, the railroad company was loath to grant any permanent rights on its property owned for transportation purposes. In this case the question was solved by the electric company purchasing in fee simple the additional property outside of the line of proposed tracks, which it had been necessary for the railroad company to secure to allow the necessary cutting and filling for the road bed construction. In addition, the electric company gave back to the railroad the right to cross its fee simple right-of-way wherever necessary to reach adjoining industrial developments and in return received certain rights to maintain wires overhanging the railroad right-of-way. (Fig. 3).

This agreement was much preferable to the revocable type previously mentioned, and was obviously a step forward in cooperation, but could hardly be called complete coordination.

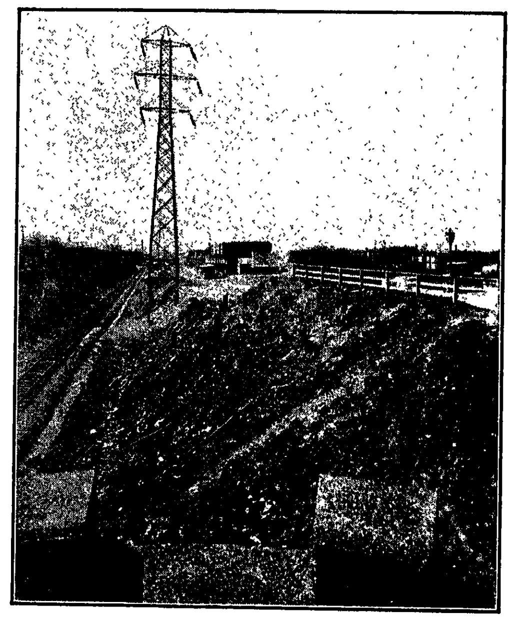

Fig. 3—66-Kv. Line Erected on Right-of-Way Purchased from Pennsylvania Railroad

When the science of electric transmission had progressed to a point where it became advisable to take advantage of the diversity existing between adjacent systems and to transmit power from outside sources into the urban area, the electric company was naturally again confronted with the same problem; that is, the necessity of either making very long and expensive runs of underground high-voltage cable or utilizing existing

railroad rights-of-way which formed the only open lanes into the congested urban sections.

The lines which have been mentioned above were of comparatively small capacity. A much more serious situation developed when it was necessary for the electric company to make plans for bringing the Conowingo power output into its metropolitan system. In this project transmission facilities had to be provided not only for Conowingo power itself but also power involved in the interconnection between the Philadelphia Electric Company, Public Service Electric and Gas Company of New Jersey, and the Pennsylvania Power & Light Company. Transmission capacity of about 600,000 kw. was required.

Obviously, it was necessary to deliver this amount of power at as high a voltage as practicable well into the highly developed sections of the city and equally obvious was it desirable to bring it in as far as possible on aerial construction. It was quite evident initially

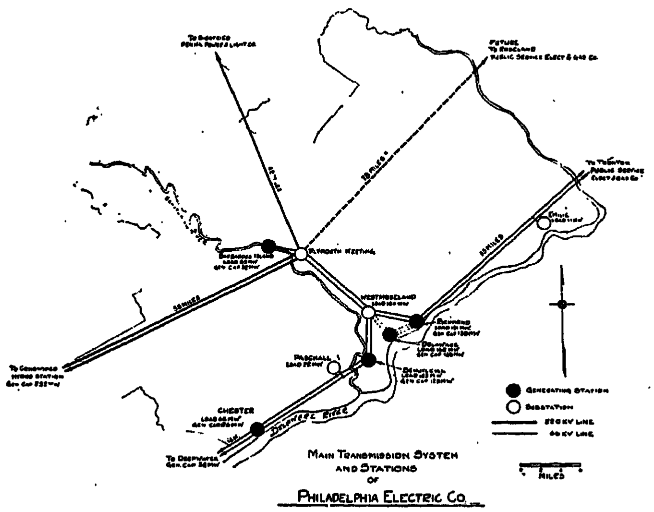

Fig. 4.—Main Transmission System and Stations of Philadelphia Electric Company

that a considerable portion of this power must be distributed to the various generating stations in the city by means of 66-kv. underground cable, but on account of the investment, this length of cable must be kept at a minimum.

The only feasible route into the highly developed territory, reaching a point which was desirable from a distribution standpoint, lay along two lines of the Reading Railroad paralleling the Schuylkill River from a point slightly inside the city limits. The latter point could be reached by the conventional aerial construction on private right-of-way. The main features of the territory and the locations of the stations is shown by the map. (Fig. 4).

The situation, therefore, required the working out of an agreement between the railroad company and the electric company which would be mutually satisfactory. Obviously, a project which formed so vital a link for such a large and important undertaking must have a permanent status and could not depend for its continuity on any revocable clause or any other consideration which did not guarantee to the electric company permanent and perpetual rights. It is equally obvious that the railroad company was in the same situation and must preserve permanent rights for maintaining its facilities in operating condition, and also, preserve the ability to change and increase its facilities as conditions required.

Occupation of railroad right-of-way for electrical transmission can in no wise be considered as similar to the utilization of public highways. The railroad company, due to its prior development, owns outright and in fee simple the major portion of its right-of-way. Consequently, it cannot give up any of the rights invested in the ownership of property or in any way limit itself in the development of its facilities.

In the situation which developed in connection with the Reading Railroad, these factors were readily appreciated in the beginning, and it was obvious that the conditions required the consideration and the finding of a satisfactory solution for the following main problems.

(a) The designing of the structures so as to provide adequate strength to meet severe conditions of climatic loading, and the existing rules and regulations of any public service body which might apply.

(b) The designing and locating the structures so that they would not interfere with the operation of the railroad company's existing or proposed tracks or other facilities.

(c) The locating and designing of the structures so that they either serve as supports for or at least not interfere with, supports for the railroad company's future electrification circuits.

(d) In the event that alteration, augmentation or reconstruction of the railroad company's facilities became necessary, the providing for a joint study of the situation to determine the most economical means of making the improvement.

(e) The reconstructing or altering of the signal and communication system in such manner as to secure satisfactory operation under the inductive coordination conditions involved, considering future railroad electrification and train control requirements.

(f) The apportionment of costs which result directly or indirectly from the occupation of the railroad company's right-of-way by the electric company's transmission circuits.

(g) The determination of a rental charge for occupation of the right-of-way.

The agreement finally reached recognized all these factors satisfactorily.

The advantages of the arrangement to the electric company are mainly that it obtains a permanent right-of-way through a district where the securing of an independently owned right-of-way would be practically out of the question from either a financial or a public

policy point of view. However, it is also evident that the electric company assumes a considerable liability.

The benefits to the railroad company are:

(a) The control and coordination of the physical and inductive conflict which might arise were the electric company's lines to be located off the right-of-way but parallel to it.

(b) Obtaining supports for its electrification transmission and catenary circuits.

(c) The alteration of all signal and telegraph facilities so that these are unaffected by the operation of the electric company's facilities and will be unaffected by the railroad's electrical operation of its trains. In this particular case the railroad's signal system was changed from direct current to alternating current and the open wire signal and communication circuits were changed to cable and placed underground, so that the railroad will be relieved of the necessity of making these changes when it electrifies.

(d) An annual rental charge for the occupation of the right-of-way.

One very important feature should be remembered. If the electric company had been obliged to purchase a right-of-way, a considerable portion of it would in this case, either have paralleled or been in close proximity

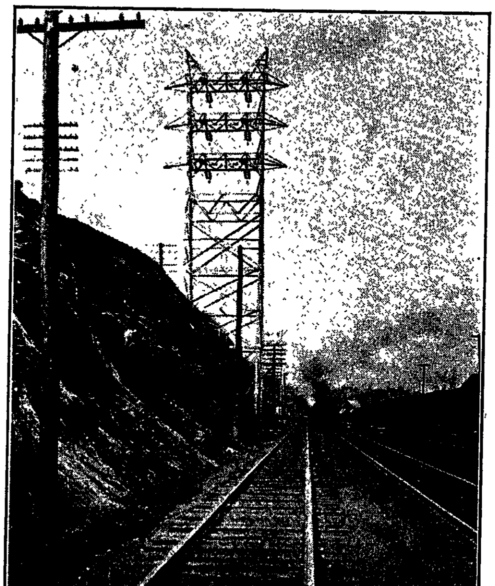

Fig. 5—Design of 66-Kv. Four Circuit Tower on Reading Railroad Right-of-Way where Space is Available Outside of Tracks

to the railroad right-of-way. In this event, while the feature of physical interference would have been decreased, the inductive interference situation would have been almost the same as exists with the transmission circuits on the railroad right-of-way. On separate rights-of-way both parties would have equal rights and a very complicated situation might have existed as to the electric company's operation of facilities which affected the railroad company's facilities.

It is not intended here to give a detailed description of the structural features as these are more of interest to the structural than the electrical engineer, so only a few points of major interest will be mentioned. Figs. 5 to 8 illustrate various types of structures and some of the typical locations.

The general electrical features for the electric company's transmission circuits are very much the same as is now the practise for 66-kv. lines on the conventional steel tower type of construction. That is, the vertical

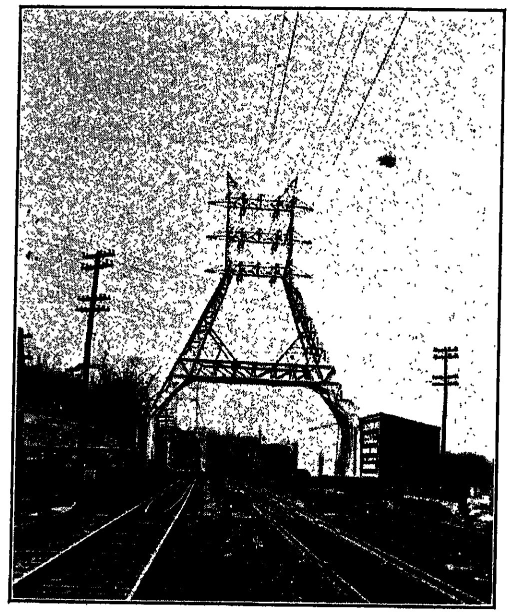

Fig. 6—Design of 66-Kv. Four Circuit Tower on Restricted Right-of-Way of Reading Company

separation between conductors is approximately 10 ft., the minimum clearance to steel work is figured at $2\frac{1}{2}$ ft. and the circuits are protected by ground wires in order to avoid lightning disturbances as much as possible.

Most parties who see either the construction or photographs comment on the fact that every span is dead-ended at both ends. This is brought about by the fact that if the usual suspension insulator had been employed in order to obtain the necessary clearance between wires and structures and between circuits the length of the cross arm, the width of the structure, necessary to support the circuits would have been so great that the wires could not have been kept within the limits of the right-of-way.

In the original installation which was made for about $4\frac{1}{2}$ miles on the Main Line and Richmond Branch of the Reading Railroad, provisions were made for 4 three-phase circuits, it being originally intended that two of these circuits would be reserved for the electric company and the two other positions reserved for the railroad company's transmission circuits for future electrification. With the further development of the railroad company's plans it proved feasible to change

the formation of the top of the structure so that on the recent Norristown Branch construction 3 three-phase transmission circuits were provided for the electric company and space for 2 two-wire circuits for the railroad company. On the newer construction it will also be noted that a bracket is provided for 36-kv. railroad circuits.

It was felt desirable by both parties to make the strength of the structure such that no question should ever arise as to their compliance with the Pennsylvania Public Service Commission's regulations covering the

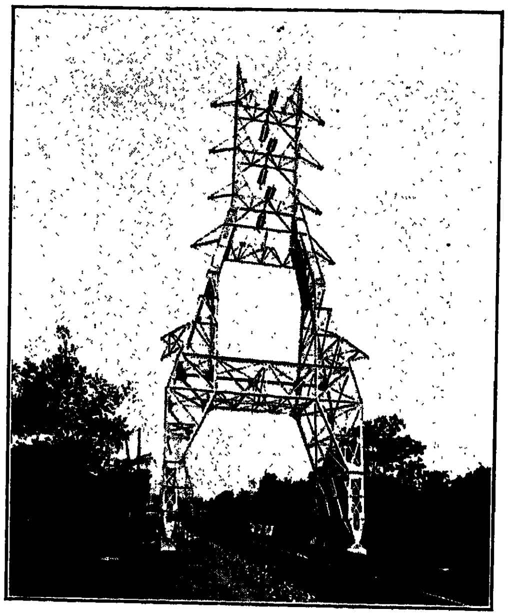

Fig. 7—Latest Type of Tower over Norristown Branch Restricted Right-of-Way of Reading Company

This provides for 3 three-phase 66-kv. power company circuits, two single-phase 66-kv. circuits for the railroad company, and two single-wire 36-kv. circuits for railroad three-wire system

strength of construction within the State of Pennsylvania. Consequently, the structures are designed to stand the full dead-end strain of the conductors on one side. While this requirement may seem very severe it actually developed during the course of detail designing that very little hardship was imposed. When sufficient strength is provided to stand the assumed design condition of all wires on one circuit being broken at the most disadvantageous location, that is, generally at the end of a cross arm, it was found that the structure was usually stronger than was required to meet Pennsylvania Public Service Commission's requirements.

In order to meet the requirements necessitated by future track construction, right-of-way, etc., several expedients were necessary in the design of structures. For the greater part of the installation on the Main Line and Richmond Branch, which is largely located on a cut on the side of a precipitate slope, there was sufficient room on the side of the cuts and fill to place the structures outside of the line of any present or proposed tracks, but as the more congested portion of the city was approached, the right-of-way conditions naturally became constricted and at some locations the conditions could only be met by a bridge type of construction which completely spanned a four track roadway. At other locations it was possible to meet the requirements by dividing the construction, placing the towers on opposite side of the right-of-way with one circuit going through the center of the structure and the other circuit overhanging the roadway.

In the construction on the Norristown Branch of the Reading Railroad the right-of-way conditions are very much restricted for about the first three miles out from the termination of the line. Throughout this section it was necessary to utilize a bridge type of construction spanning a proposed four-track roadway. A proportion of this roadway was involved in a grade crossing elimination project and several various interesting situations were involved.

In certain portions a retaining wall was to be built and the design of the foundations for the transmission structures was necessarily coordinated with the design

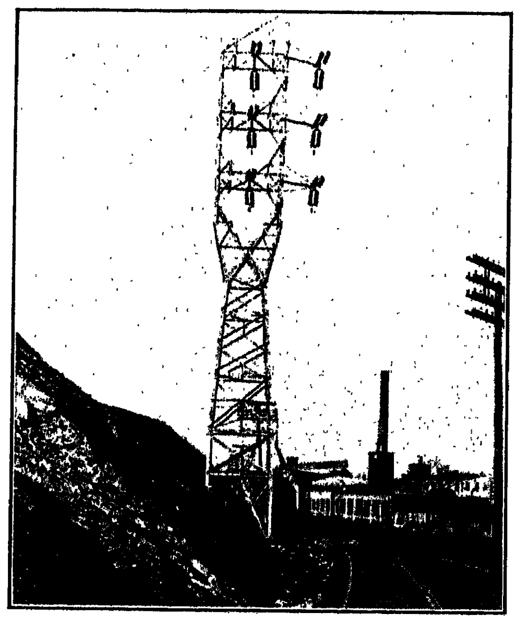

Fig. 8—Design of Special Two-Circuit Tower on Side of Reading Tracks

Two additional circuits will be provided by similar construction on other side of tracks

of the retaining wall. Consequently, the tower footings formed portions of this wall. At another location a steel viaduct was to be constructed and the viaduct was so designed at the necessary location that the steel work for the transmission structures could be attached directly thereto.

At certain other locations where the actual railroad right-of-way was of insufficient width it was found preferable and cheaper to purchase additional right-of-way rather than to adopt the more costly bridge construction.

By the time this paper is presented one circuit of the new construction should be in operation, the initial construction having been in operation somewhat over two and one-half years with very satisfactory results. Throughout this two and one-half year period the two initial circuits have, at times, carried as high as 200,000 kw. In fact, they have continually carried, except for some 20,000 or 30,000 kw. which is diverted at Plymouth Meeting substation either to the Pennsylvania Power & Light Company's system or to Barbadoes Island plant at Norristown, practically the entire output of the Conowingo plant. During the present year interconnection is to be completed with the Public Service of New Jersey which will, to a certain extent, increase power flow both into and out of Philadelphia Electric Company's system at various times of the day.

The transportation of coal from the mines to our urban centers of population and of electrical energy from the sources of hydroelectric supply to these same centers affect all industry, and directly, or indirectly, a large proportion of the country's population.

The more intensive use of right-of-ways for the transportation of these commodities and the successful coordination of the problems involved is a tribute to the managements of the respective companies. Cooperation of this kind can not but result in substantial benefits to the public.

Discussion

Sidney Withington: This paper presents clearly the growing recognition of the fact that many problems which were formerly attacked individually are now recognized as joint problems among those whose duty is that of service to the public. Among other examples, are the problems of electrolysis, inductive coordination between power and communication circuits, and the joint use of wood poles among public utility companies. It is of interest to note that both parties to the arrangement under discussion are thoroughly satisfied. This speaks well for the spirit of the officers of both companies. Such cooperation reacts to the benefit of each company and through it to the public it serves.

Item "g" of the factors involved mentioned by the authors calls attention to rental charged for the occupancy of the railroad right-of-way. It is true that in other instances where such problems are met, the railroads may set an unduly high value on their rights-of-way as potential routes for other utility companies but it is also true that power companies sometimes express the thought that inasmuch as the railroad right-of-way exists and there seems to be room to spare, they should be allowed to locate their lines without obligation to pay any rental. Agreement upon a figure fair to both sides seems sometimes to be rather difficult.

In locating a high-tension line along and over railroad tracks it must be recognized by all concerned that there is introduced a hazard both to railroad operation and to the power facilities, which would not otherwise exist. If a derailment occurs which wrecks a tower and brings the high-tension circuits down upon the train, somebody must assume the responsibility. If the transmission line had not been within reach, the power supply would not have been interrupted, and conversely there might have been less property damage or personal injury to the railroad and its patrons if the transmission line had been absent.

It would be of interest to know what arrangements are made for patrolling and maintenance of the transmission line. Does the railroad allow the employees of the power company to use a car for patrolling purposes and for transporting labor and material or is there sufficient access from highways to the right-of-way at all points to make this consideration unnecessary?

The last paragraphs of this paper bring to mind an interesting picture—that of the transportation of energy along railroad right-of-way in the form of electric power rather than in the form of coal. The railroads are losing a great deal of passenger and freight traffic to highways and canals, to the construction and maintenance of which, incidentally they are obliged to contribute largely. The railroads cannot afford much further impairment in gross revenue without perhaps radical reconstruction of their rate structures, as many of their fixed expenses are independent of traffic. I believe railroads as a whole will look with some concern upon further loss of their load.

W. W. Woodruff: Mr. Withington asks information as to the use of the railroad right-of-way for patrolling and maintenance of transmission lines. In this particular case, the right-of-way is to a large extent sufficiently accessible from highways to make it unnecessary to use the railroad facilities for any ordinary maintenance or repairs. Also, the distance is so short that inspection or patrolling is, from a transportation standpoint, a very minor matter and can easily be done on foot.

A question is raised as to the reduction in railroad revenue resulting from the transportation of energy along the railroad right-of-way and the consequent reduction in coal tonnage. This is a question concerning which I choose to express only a very general personal opinion.

Everyone remembers the old cartoon showing two calves with two pails of milk; both calves trying to drink out of the same pail, with very poor success, while the other pail stands untouched. This applies rather pointedly to the thought expressed.

Translated into economic terms, the lesson is that the attempt by any organization, railroad or other, to block the advance of economic progress, in order to avoid the loss of a present advantage, is not in line with sound economic policy and doomed to eventual failure. Economic situations are always changing and are governed by factors entirely outside the control of any individual industry and any artificial measures introduced or old methods adhered to for the purpose of maintaining the *status quo* only postpones the evil day and makes the final readjustment more severe. A great many very disagreeable situations could have been avoided by recognizing this principle, and proper cooperation between various industries, before the time the situations became acute, could have resulted in benefits to all, rather than dissipating valuable assets.

Initiation of an Electrification Into Operation

BY H. C. GRIFFITH[1]
Non-member

Synopsis.—This paper describes the energizing and putting into service of the Pennsylvania electrification project. The normal and desirable procedure of placing an electrification into service is cited, and the departure from it brought about by the difficulties encountered in actual railway operation are explained.

The operating practise—functions of the power director, his assistants, substation operators, and foremen in connection with switching operations, grounding circuits, carding of circuits, and manner of obtaining releases—is described and illustrated. All of this is very essential to properly coordinate the work and safeguard the personnel of the construction forces, operating forces, and test men during the transition period of completion and placing into operation a railway electrification project.

* * * * *

THE recent completion and placing in service of the Pennsylvania Railroad's electrifications between Philadelphia and Trenton, and Philadelphia and Norristown, has emphasized the importance to the railroad of the transition stage which turns a construction job into an operating job, and which has been called initiation into operation.

The normal and desirable procedure on an electrification construction job would be to complete the construction work with the construction forces, release the construction men, and turn the project over to a test organization who would then energize the various circuits and apparatus and make all necessary potential tests, check control operations, protective relay operations, automatic switching sequences, etc.

Unfortunately, a major electrification project which when completed becomes a part of an electrification system already in operation can seldom follow this logical sequence. The management which has authorized the large expenditure naturally wants the operation to start at the very earliest possible date in order to obtain promptly the benefits for which the project was authorized. This necessitates the overlapping of the test period with the completion of the construction work, and results in having the construction forces working on portions of the circuits and apparatus while other portions are being energized and tested.

The situation is complicated further by the fact that the operating department requires a portion of newly electrified tracks turned over to them for a period before completion, for the operation of special electric trains for the training of crews. Also, if the project involves changing to a new transmission and distribution system for signal power, as was the case in the Trenton and Norristown electrifications, this supply of power must be available some time before completion of the construction work so that the signals and interlockings can be changed over prior to beginning of the operation. This results in having energized signal equipment, transmission, and trolley lines to contend with prior to the release of the construction forces.

To render this transition period as safe as possible for the construction force and others involved, when work of construction on and around apparatus at times energized to a high potential for testing and training operations was necessary, a general plan was prepared and adopted.

The section being electrified was divided into three or four divisions, using points where the circuits were sectionalized as limits. The section which it was desired to energize first was taken as No. 1, the second as No. 2, etc. The construction work program was then so arranged that in so far as possible No. 1 section would be pushed forward to completion—if necessary at the expense of the others; No. 2 would follow, and so on. This reduced to a minimum the amount of work the construction forces had left to do after the section in question had been energized, but did not entirely eliminate it, as test operation developed poor alinement of trolleys, hard spots in the catenary system, errors in substation wiring, and the need for readjustments in switches and circuit breakers.

A definite date and time was then set, after which all wires and apparatus in the first section should be considered energized to high potential at all times. The division superintendents were requested to issue a general order to be posted and signed for by the railroad employees, advising them of the exact time and the territory within which all overhead wires, substations and equipment must be considered energized.

A similar notice was forwarded to the superintendent of the construction forces, who was requested to have each man in his organization sign as having read and understood the notice.

The same thing was done for the field engineering and testing organization.

No voltage was applied to any of the equipment in each particular section until after the date and time specified in the notices applying to that section.

Prior to the date for energizing, various employees of the operating department were given a time allowance to go over in detail the new electrification project in order to become familiar with every phase of it. They were also given prints showing the arrangement and details of circuits. During this time allowance, they were expected to absorb sufficient information to enable them to pass a thorough examination to qualify in the particular class of work which they would be expected to perform when operation began; that is, the em-

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ployees who would operate as power directors were expected to learn thoroughly all phases of the project necessary in the transaction of business as power directors; the substation maintainers and inspectors to qualify along the line of their duties and the linemen along their special line. Each one was given a detailed examination by the supervisory force and was expected to pass this examination in a satisfactory manner.

A short time prior to the date and time specified in the

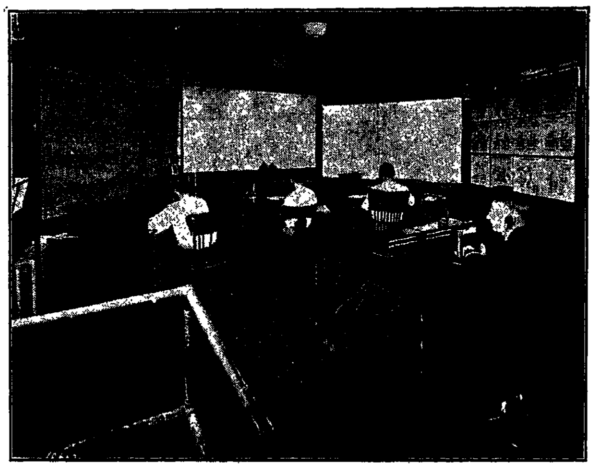

FIG. 1—POWER DIRECTOR'S HEADQUARTERS AT WEST PHILADELPHIA SUBSTATION

General Notice issued, the power director was put on duty at the regular control headquarters to handle the energizing and testing of the new electrified section. A second and third trick power director were also

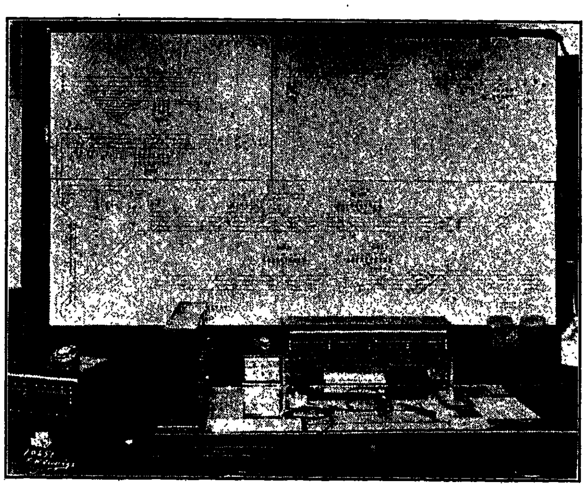

FIG. 2—DETAIL OF PLUG BOARD

Showing arrangements of trolleys and cross-overs with plugs at sectionalining and supply points

assigned so that for the full 24 hours each day, each move of energizing various circuits and apparatus and testing of same was done under the control of a properly qualified man.

Qualified substation operators were placed in each substation of the section covered by the order, to take out clearances and ground all high-voltage circuits or apparatus on which construction work remained to be done. The protection of the construction force in each particular substation was made the definite duty of these men, and in a number of cases it was necessary to supply qualified substation men for each of the three tricks in the 24 hours of the day.

In a similar manner a qualified lineman was assigned

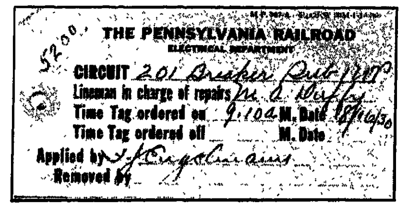

FIG. 3—STANDARD CLEARANCE TAG TO BE APPLIED TO REMOTE-CONTROL HANDLE FOR OPERATING SWITCH

to each construction wire train, transmission gang, gang installing bridge protection, and each other gang whose duties involved its working over or around energized circuits. When necessary, in order to permit construction work to be performed after portions of the electrification had been energized, these qualified linemen would take out clearances and ground circuits for the performance of work by the construction gangs on or in close proximity to energized circuits.

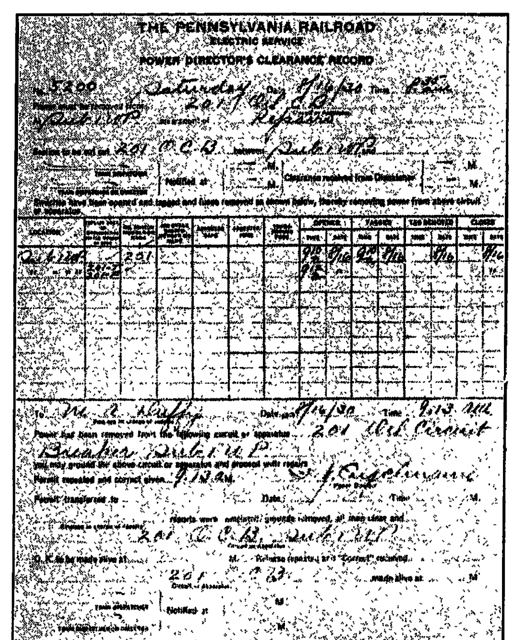

FIG. 4—CLEARANCE RECORD PREPARED BY POWER DIRECTOR FOR EACH CLEARANCE ISSUED

The power director referred to above is located in the West Philadelphia Substation and has complete jurisdiction over the operation of the electrical circuits and apparatus on the section of the electrification to which he is assigned. This is illustrated in Fig. 1. In case of faults developing on any portion of the system, it is his duty to restore power at the earliest possible moment. In case a fault continues, he so sectionalizes

the system that the portion of the system out of service is reduced to an absolute minimum. He must deal with the train dispatcher in the handling of trains in the electrified zone so that restrictions in train operation and

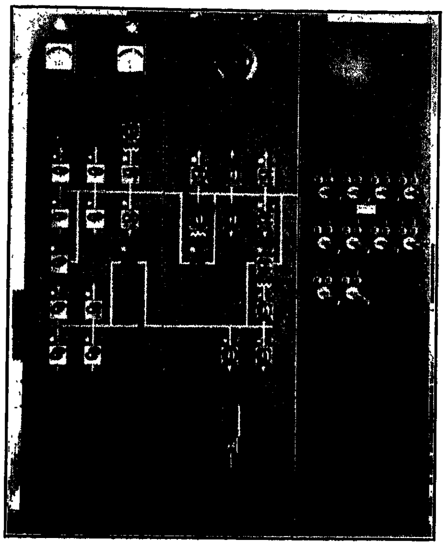

FIG. 5—CONTROL BOARD

Showing remote-control handle blocked out and clearance tag applied to three control handles

the interruptions to train schedules are reduced to a minimum.

In case of a defective section of trolley developing, he must instruct the train dispatcher as to the condition

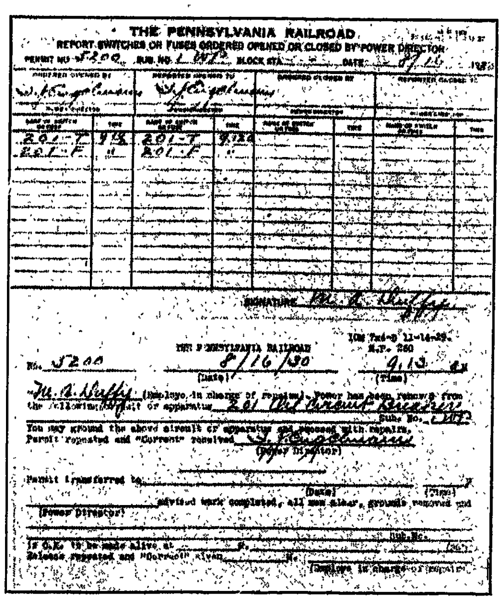

FIG. 6—OPERATION REPORT FORM

Upper half—Standard switching blank filled out by operator

Lower half—Standard clearance blank filled out by qualified workman taking out clearance

existing in order to prevent the operation of trains into the defective section.

The responsibility for cutting out certain circuits or apparatus for normal maintenance is also a part of his duties. He selects the proper switches to be opened in order to remove power, and instructs the various operators usually located in the signal block towers, to open these switches and tag them prior to issuing the clearance to the qualified workman who performs the work. (Fig. 2.)

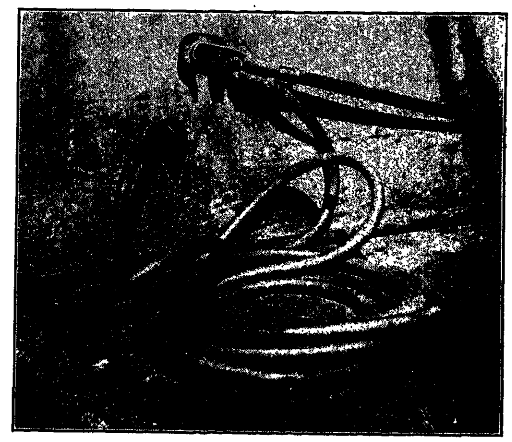

FIG. 7—STANDARD GROUNDING STICK

Showing clamp for conductor and clamp for ground connection

After the operator reports to the power director that proper switches have been opened and tagged with the name of the workman to perform the work, as ordered by the power director, the power director then issues to the qualified employee in charge of doing the work a

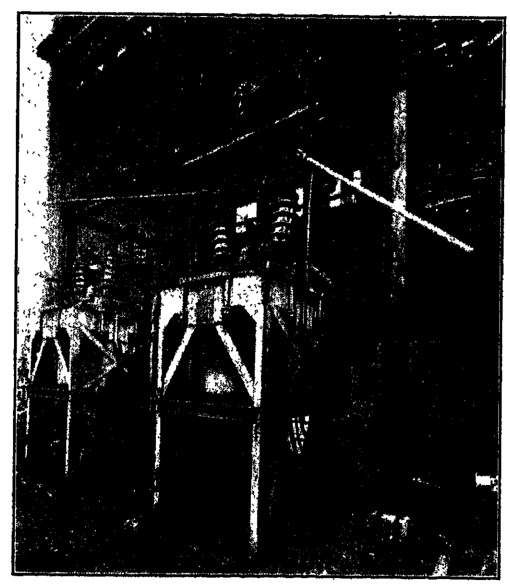

FIG. 8—GROUNDING STICKS APPLIED TO HIGH-SPEED TROLLEY CIRCUIT BREAKER

formal clearance. (Figs. 3 and 4.) The switches thus tagged must never be closed until the removal of these tags at the instruction of the power director has been accomplished.

The power director is forbidden to order closed any switches, on which a clearance has been issued, prior to the formal release of the clearance by the qualified employee to whom it has been issued.

This rather elaborate formality has been found necessary to prevent the accidental closing of any switches energizing circuits on which men are working

and has proved to be an adequate safeguard. (Fig. 5.)

Where qualified substation operators and linemen are required to operate outlying disconnecting and sectionalizing switches not controlled from a remote control board, these operations must be performed only under definite instructions from the power director and a proper record kept on a switching report blank. The switching report blank and the clearance blank when completed must be forwarded at once to the operating headquarters for filing. The power director's record and the qualified employee's record of the clearance issued are checked and must be similar in all details. This checking is done periodically to prevent the development of carelessness on the part of any of the men involved in the handling of the clearances. (Fig. 6.)

After the qualified employee has received his clearance, before beginning work on energized equipment or circuits, he must apply the standard ground sticks which are supplied for that purpose. Upon completion of the work, these ground sticks must be removed before formally giving up the clearance under which he is working. (Fig. 7.)

The ground sticks are designed with a clamping hook on the end of a pole and an extremely heavy cable connecting to a clamp which clamps to a grounded connection or structure. Experience over a number of years has definitely proved that if these sticks are properly applied, the workmen will at all times be fully protected, not only from accidental energizing of circuits, but also in case of mistake in segregating the circuit or apparatus and the power not being removed. Ground sticks as illustrated in Fig. 8 have been applied to high-voltage circuits while energized without damage to the equipment or injury to the man involved.

The above general procedure has been reviewed in order to show the safety precautions found necessary in the handling of a major electrification project. It has been the experience that in spite of all precautions and safety features, accidents around high-tension circuits will happen and every effort must be made at all times to keep those directly involved in their operation thoroughly familiar with these hazards and compel strict adherence to all safety regulations. There is no period to which this applies more strongly than it does to the period of initiating electrical operation and closing out the final details of the construction work.

Discussion

Sidney Withington: Mr. Griffith calls attention to the haste on the part of railroad managements to place facilities in operation at the earliest possible moment as they approach completion. When it is considered that the capital charges against any given project begin as soon as expenditures start and that they are a direct function of the money expended, it is readily seen that these charges may reach to a very considerable sum per day when an installation of several millions of dollars is involved. Any time saved in placing the facilities in revenue service represents real money and is worthy of considerable effort.

Mention is made of the relations between the power director or load dispatcher and the train dispatcher. It is obviously very necessary for these two positions to function with the closest cooperation and when it can be accomplished without too much sacrifice it may be desirable to locate the two men in the same or immediately adjacent offices. The most reliable communication facilities are of course essential in any event, for defective communication inevitably means delay to train operation.

One of the outstanding characteristics of work on railroad power circuits having rail return is the absolute protection which each man has by the application of the ground stick described by Mr. Griffith. With this device the men working on such circuits are absolutely safeguarded in event of accidental energizing of the circuit. Each man can be made entirely and personally responsible for his own protection.

It would be of interest if Mr. Griffith were to mention the routine followed by the line crews after they have obtained a circuit upon which to work. Is the foreman provided with blank forms to fill out for the information of the linemen? On the New Haven Railroad the foreman gives to each lineman in his gang a carbon copy of a memorandum which states specifically what circuits have been deenergized and grounded. This does not relieve the individual lineman of responsibility for personally seeing that the ground stick is applied, but the act of the foreman writing out the information and the act of the individual lineman in receiving it, we feel, impresses the situation upon the minds of both and is of psychological value.

H. C. Griffith: The procedure followed by the line foreman in obtaining his circuit on which to perform work is as follows:

He telephones the power director, requesting the particular circuit desired, advises the general nature work to be performed and gives a close estimate of the length of time required. The power director, if conditions are suitable, orders open and tagged the proper switches to segregate and deenergize the circuit in question. He then issues a formal clearance to the line foreman who repeats same back to the power director. The foreman then advises each of his men the particular circuit or circuits on which he holds a clearance and points out the adjacent circuits that are not deenergized.

The grounded pantograph on the wire train is then raised to contact with the circuit and ground sticks installed on each side of the wire train. Each workman has definite instructions that he must personally insure himself that proper grounds have been installed before he proceeds with his portion of the work. At the completion of the work, the foreman checks that each individual lineman is clear of the circuit, that grounds have been removed and advises each man that the clearance is being given up, and the circuits must be considered energized.

The foreman then formally releases his clearance to the power director who then orders the necessary switches closed to energize the circuit and restore normal set up.

The Modern Single-Phase Motor for Railroad Electrification

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Associate, A. I. E. E.

and

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Synopsis.—*The past three years have seen a great increase of activity in the field of alternating current electrification of steam railroads and, consequently, much attention has been given to the design of the single-phase traction motors upon which the success of this type of electrification chiefly depends.*

The object of this paper is to describe the up-to-date motors which have been developed to meet the requirements of modern American railroading.

IN order to meet the demands on traction motors incident to announced single-phase electrification programs, considerable developmental work has been done.. Sample motors were built and extensively tested and a sample multiple-unit car was completely equipped and put into regular passenger service.

"TRANSFORMED" VOLTAGE

The biggest handicap that besets single-phase commutator type motors lies in the presence of an alternating voltage between heel and toe of the brushes, which

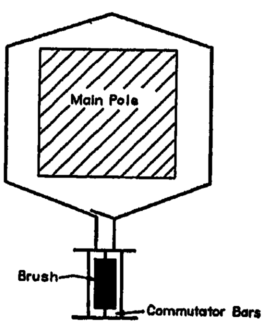

FIG. 1—DEVELOPED VIEW OF AN ARMATURE COIL UNDERGOING COMMUTATION IN ITS RELATION TO THE FACE OF THE MAIN POLE

can be corrected at speed but which cannot be avoided at standstill.

This is illustrated in Fig. 1 which shows an armature coil undergoing commutation.

The torque field winding which is in series with the armature produces the torque flux. This flux instead of being constant, as in d-c. motors, is alternating and induces by transformer action a certain voltage in each armature turn. This "transformed" voltage has the maximum amplitude in the coils short-circuited by the brushes since the plane of these coils is at right angles to the direction of the flux.

With a sinusoidal flux wave of 25 cycle frequency, the r. m. s. voltage induced in these coils is:

Transformed voltage per turn = 1.11 ϕ maximum, where ϕ maximum is the maximum amplitude in megalines of the torque flux. If the brush short-circuits two adjacent turns, that is, if it touches three commutator bars, the voltage which is impressed between heel and toe of the brush is twice the voltage induced in each turn.

The transformed voltage is 90 deg. out of phase with the flux, that is, with the motor current.

STARTING COMMUTATION

We will first discuss standstill or starting conditions: Fig. 2 shows what happens to a typical brush between heel and toe of which an alternating voltage is impressed. A brush of the size used in the test normally carries a load current of 50 amperes and under overloads will carry up to twice that current.

If a heel-to-toe voltage is applied continuously, glowing will occur from about 2.5 volts up, and the glowing will be become very violent above the knee. Severe pitting and softening of the commutator bars will occur.

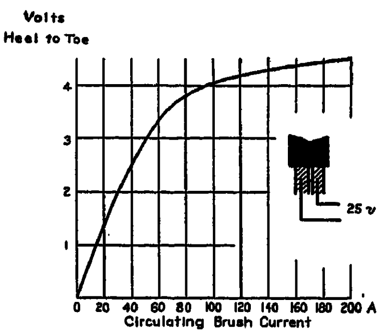

FIG. 2—BRUSH VOLT-AMPERE CHARACTERISTIC

It is obvious that this condition, as far as its effect on the commutator bars is concerned, is most pronounced at standstill.

The curve shown in Fig. 2 was taken without any load current flowing through the brush; the presence of a load current increases the circulating current at any voltage.

PRACTICAL LIMITATIONS OF THE TRANSFORMED VOLTAGE

Earlier designs of single-phase traction motors used heel-to-toe voltages of 10 volts or more and the present motors use values which are, roughly, half these.

It will be seen from the above that even these lower

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voltages, if maintained indefinitely, would damage the commutator. However, the operating experience abroad and the experience so far gained in this country with motors designed for these new constants indicates that, in service, the actual time during which these excessive circulating brush currents flow is well within safe limits.

Thus, it is seen that the design of a single-phase traction motor will largely hinge around the necessity of keeping the transformed voltage, from heel to toe of the brush, down to a permissible figure. In the motors under consideration, the brushes cannot short-circuit more than two coils and the transformed voltage per turn at standstill does not exceed 3.25 volts for the locomotive motors and 2.75 volts for the multiple-unit car motors.

Number of Brush Holders

These values of transformed voltage per turn at standstill determine the flux per pole under starting conditions. The torque of a motor is proportional to the product:

Total armature ampere-conductors times number of poles times the flux per pole.

The last term of this product is determined as we have just shown. Thus, we see that for an armature with a definite ampere-conductor loading, the starting torque goes up directly with the number of poles, or, in other words, with the number of brush holders.

Commutator Constants

As a matter of fact, the short-time loading of an armature is limited more rapidly by the load current density in the brushes than by the current density in the armature conductors themselves.

In order to bring out this limitation in the formula which gives the torque, we will express the total armature ampere-conductors as:

Total conductors times amperes per brush holder or, what amounts to the same thing:

Total conductors times current density in the brushes times commutator length times brush thickness.

If we substitute the above expression in the torque formula, we find that the latter is proportional to:

Total conductors times current density in the brushes times commutator length times brush thickness times poles times flux per pole.

It should be understood that all single-phase traction motors have armatures wound with one turn per coil; also, that the brush thickness is generally taken as twice the commutator bar pitch.

Hence, the brush thickness is generally proportional to the expression:

$$\frac{\text{Commutator diameter}}{\text{Total conductors}}$$

Substituting this expression in the last product, we find that the starting torque is proportional to:

Commutator length times commutator diameter times poles times current density in the brushes times flux per pole.

The last two terms are determined by the characteristics of the brushes; thus, we see that the starting torque which can be obtained from a single-phase traction motor is proportional to the area of commutator and to the number of brush holders.

For a given commutator diameter the new motors have from 50 to 100 per cent more brush holders than earlier motors and, as the disturbance at the commutator is proportional to the square or to some higher power of the flux per pole, the starting commutation is greatly improved.

Running Commutation

When the motor is running we must deal with two elements of commutation:

The a-c. or *quadrature* element of commutation, caused by the transformed voltage, is still present and we will show how this element can be effectively compensated; also, we are dealing with the *in-phase* or *rotational* element of commutation which is of the same nature as the sparking reactance voltage in a d-c. motor.

The modern single-phase traction motor has, in addition to the torque field winding, a compensating winding and an interpole winding. These two windings together neutralize the armature reaction very effectively; the compensating winding neutralizes the armature reaction under the main poles and effects a considerable improvement in commutation and power factor over that which would be obtained if the same number of ampere-turns were concentrated around the interpole. The interpole winding neutralizes that portion of the armature reaction which is in excess of the compensating winding ampere-turns and in addition provides a surplus of ampere-turns. This surplus produces a flux under the interpole which develops in the coils undergoing commutation a voltage to neutralize the reactance voltage induced by the reversal of the current, exactly as in a d-c. motor.

Rotational Element of Commutation

It should be strongly emphasized that the commutation of a single-phase motor can be no better on alternating current than it is on direct current. Consequently, in order to design a good a-c. commutator type motor, it is indispensable to put into it, first, all the elements which give good commutating characteristics to a multiple-wound d-c. motor, such as the following:

For the armature:

An odd integral number of slots per pair of poles,

An odd number of turns per slot,

A back-end winding pitch other than a multiple of the number of slots,

Sufficient fractional pitch to minimize the mutual inductance of coils undergoing commutation,

Adequate equalization.

For the stator:

A correct design of interpole having a face which properly covers the commutating zone backed up by a core dimensioned practically to obviate saturation,

Adequate neutral space between interpole and main pole tips.

For a better understanding of the rotational element of commutation in a single-phase motor, let us consider the variations of the current in any armature conductor, as illustrated in Fig. 3.

Assume that the peripheral speed of the commutator is 6,000 ft. per min., that is, 1,200 in. per sec., and that the brushes are 3/8 in. thick. The reversal of the current takes place in the time that it takes for a point on the commutator to pass a brush less the thickness of a mica, that is, in:

$$\frac{0.375 - 0.030}{1200} = \frac{1}{3500} \text{ second.}$$

With a 25-cycle power supply each alternation lasts 1/50 sec. In other words, the current reversal in commutation is 70 times faster than the reversal due to the alternating supply. If we look at a sine wave and pick two points $\frac{180 \text{ deg.}}{70} = 2\frac{1}{2}$ deg. apart, we realize that there is very little difference between their ordinates. In other words, during the time that a coil is short-circuited by a brush, the motor current varies so little that it might just as well be direct current. Fig. 3 also shows that, at normal speed in the example chosen, the frequency of commutation (250 reversals a second) is much higher than that of the supply. In other words, the fact that we are dealing with 25 cycles should not affect materially the phenomenon of current reversal which is 70 times faster and which occurs 10 times more frequently.

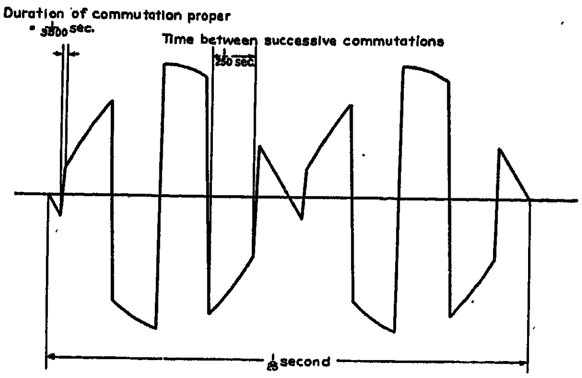

FIG. 3—VARIATIONS OF THE CURRENT IN ONE ARMATURE CONDUCTOR

From the above, one could expect approximately the same excess ampere-turns in the compensating and interpole windings to commutate 25-cycle alternating current as to commutate direct current. This has been proved very conclusively by test.

TRANSFORMED ELEMENT OF COMMUTATION

To accomplish the compensation or neutralization of the transformed element of commutation, an external resistor shunting the interpole winding is used.

The current in the resistor leads the line current and the current in the interpole winding lags behind it.

Fig. 4 shows how the current in the interpole winding has two components; one, in phase with the line current, the magnitude of which is adjusted to take care of the rotational element of commutation, and one, 90 deg. out of phase with the line current. This latter

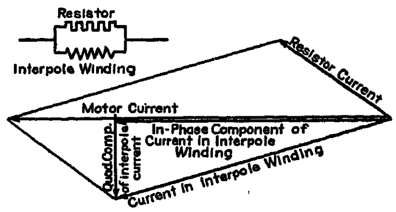

FIG. 4—VECTOR DIAGRAM ILLUSTRATING THE PHASE SHIFT OBTAINED BY THE USE OF THE SHUNTING RESISTOR

component produces a flux which, by virtue of rotation, generates a voltage in the coils undergoing commutation, in this same phase relation, that is, 90 deg. out of phase with the line current. This opposes the transformed voltage both in phase, and, for definite speeds, in magnitude.

The simplicity of this scheme has given it a very wide application and practically all modern single-phase traction motors make use of it.

Theoretically, this scheme accomplishes a correct neutralization of the transformed element of commutation at all loads but only at one speed because the neutralizing voltage is proportional to the speed while the transformed voltage is not affected by the speed at a given load.

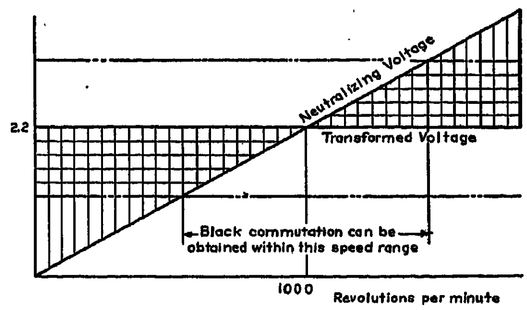

FIG. 5—EFFECT OF SPEED ON THE NEUTRALIZATION OF THE TRANSFORMED ELEMENT OF COMMUTATION

Transformed volts per turn. The shaded areas denote under or over compensation

Fig. 5 illustrates this condition for a motor which is correctly compensated at 1,000 rev. per min. Below this speed there is a condition of under-compensation which is, of course, most pronounced at standstill. Above this speed there is over-compensation.

The fact should be kept in mind, however, that it is not necessary to have quite perfect neutralization in

order to obtain black commutation since it takes a certain voltage to produce a spark across the copper-brush contact. The two horizontal lines drawn above and below the line of ordinate 2.2 volts give an idea of the range of uncompensated voltages within which black commutation can be obtained. The lower the flux per pole, the wider is the corresponding speed range. Thus, improving the starting commutation also improves the running commutation.

Commutation Settings

It can be seen now how it is possible to segregate and correct the rotational and the transformed elements of

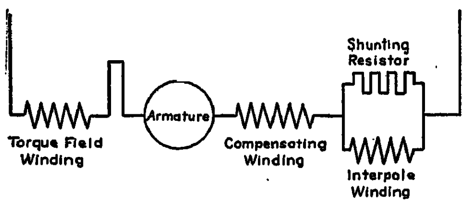

Fig. 6—Diagram of Connections of a Single-Phase Traction Motor

commutation in order to obtain black commutation over a wide range of speeds and loads. This consists in the adjustment of the number of turns of the interpole winding and of the value of the shunting resistance.

For motors required to operate over a very wide range of speeds and loads, two commutation settings are used. A change in the value of the shunting resistor and the introduction of a reactive shunt are effected by the control switches. Locomotive motors re-

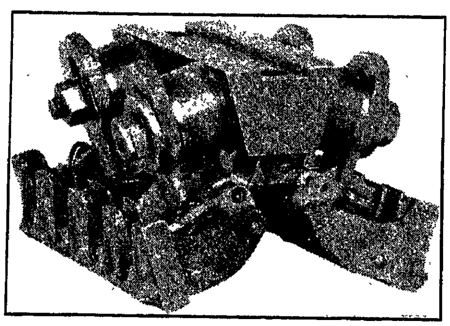

Fig. 7—Brush Holders and Supports with Micalex Insulators

quired to develop full rated horsepower up to the maximum operating speed come in this class.

The losses in the shunting resistor vary from one to two per cent of the motor input, the lower figure applying to the larger size and higher speed motors.

Diagram of Connections

The diagram of connections of the modern single-phase traction motor is a very simple one. All windings are in series; the shunting resistor is permanently connected across the interpole winding and there is no change in motor connections throughout the operating cycle.

Motor Voltage

Because of the limitation of the flux per pole, the single-phase traction motor is, inherently, a low-voltage machine. For example, the rated voltage of a locomotive motor is 225 volts and that of a multiple-unit car motor with a lower flux per pole is 170 volts.

If similar constants of design are used (flux per pole, commutator peripheral speed, commutator bar pitch) the voltage of machines of different sizes will be the same regardless of the number of poles and brush holders.

Power Factor and Efficiency

At their continuous rating, these motors have a power factor of approximately 95 per cent and an efficiency at the shaft of 85 to 90 per cent, the higher efficiency figures applying to the larger size and higher speed motors.

Field Shunting

Under severe starting conditions it may be advisable to weaken the main field at starting, preferably by

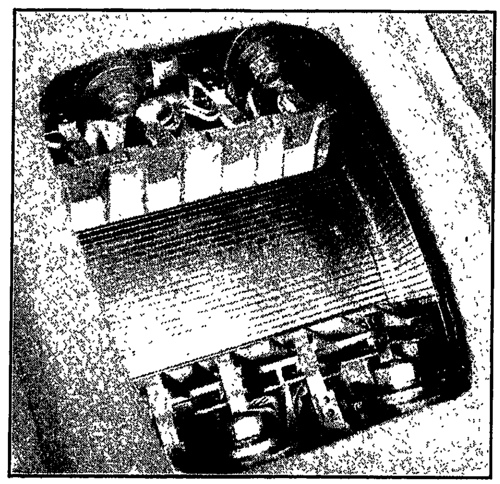

Fig. 8—View Showing the Accessibility of Brush Holders

means of a saturated inductive shunt, in order to keep the flux, and, hence, the transformed voltage, below a certain limit. In this case, the motor must draw a heavier current to develop the required torque but there is a net gain in commutation.

In some locomotive equipments being built the connections are changed from weak field to full field by means of a control relay which operates as a function of the locomotive speed. The relay is set to operate at the speed at which the commutation in the full field connection with its lower load current equals the commutation in the weak field connection with its lower transformed voltage.

Motor Construction

These features of design have been worked into a 1,250-hp. twin-armature locomotive motor and a 220-hp. axle-hung multiple-unit car motor, the construction of which is shown by the illustrations on these pages.

Brush Holders

In order to find room for the larger number of brush holders, provide proper clearances and allow for easy inspection and renewal of brushes, a new design of brush pressure finger has been worked out. At the same time, much greater uniformity of brush pressure as between new and worn brushes was incorporated in

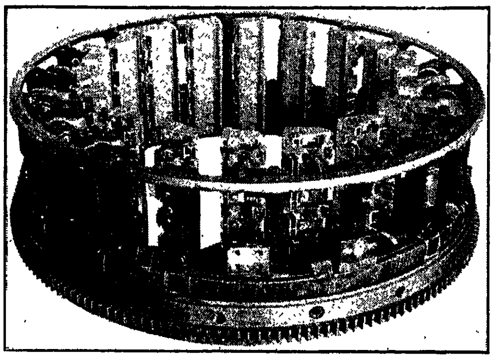

Fig. 9—Brush-holder Yoke for 1,250-Hp. Twin Armature, Locomotive Motor

the design and more accurate spacing of brush holders has resulted.

The brush holder and supports shown in Fig. 7 have been applied to the motors on the sample multiple-unit car previously referred to and Fig. 8 illustrates their accessibility. Their performance in actual service

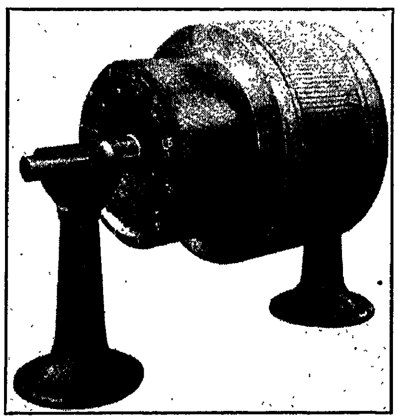

Fig. 10—Rotor of 1,250-Hp. Twin-Armature Locomotive Motor

has been very gratifying; no trouble whatever has developed, the commutators run with a highly polished surface and the very small brush wear indicates at least two years of brush life.

The locomotive motor brush-holder yoke shown in Fig. 9 is arranged to revolve by means of gearing to facilitate inspection from one opening in the motor frame.

Armature

The armature winding is made up of folded cross-over bars which minimize eddy currents. The joints at the back end are silver soldered. There are three coils per slot and the armature slots are spiraled one-half slot pitch to minimize telephone interference and to smooth out the interpole flux. Fig. 10 shows a complete rotor.

Stator

Fig. 11 shows the 18 main poles and interpoles in each stator of the twin locomotive motor.

All stator windings are composed of rectangular conductors wound into coils of the requisite number of turns, insulated with mica tape and introduced into the slots through the slot openings. The slots are closed with bakelized canvas wedges. The coils of each circuit are connected in multiple to bus-rings by means of

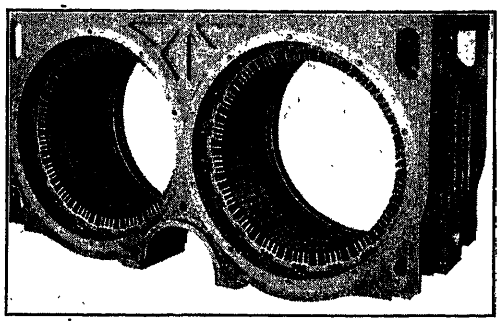

Fig. 11—Frame of 1250-Hp. Twin-Armature Locomotive Motor with Stator Punchings Ready to Receive the Stator Windings

silver-soldered joints. After winding the stator is impregnated by the vacuum process with an insulating and water-proofing compound.

Bearings

The modern single-phase motors use grease-lubricated anti-friction bearings resulting in reduced bearing maintenance and maintaining uniform air-gaps which are of considerable aid in commutation.

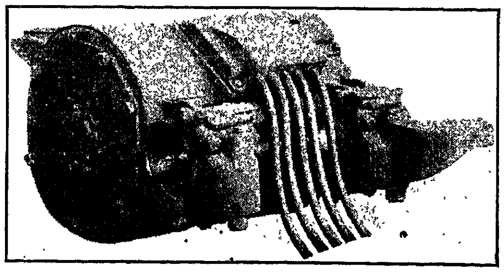

Fig. 12—215-Hp. Multiple-Unit Car Motor

Capacity

The horsepower capacities of these motors compare very favorably with those of d-c. traction motors of similar weight. For example, a 220-hp. multiple-unit car motor weighs 5,600 lb. and a 625-hp. freight locomotive motor weighs 14,000 lb. These weights do not include the gear, pinion, gear cover and axle linings.

CONCLUSION

It will be noted that in the attempt to improve the single-phase motor the greatest effort has been applied to the commutation at starting. Fortunately, this also aids the commutation at speed.

The other problems encountered in the design and construction of single-phase motors are similar to those met with in all other kinds of traction motors.

With this very material improvement in commutation, the single-phase traction motor can be counted upon to give good reliable service with low maintenance cost.

Discussion

C. E. Skinner: The paper forms an interesting presentation of the relations that exist in the single-phase series commutator motor and the successful results indicated are notable.

The fundamental principles have been rather well known. In an address in February 1908 Mr. B. G. Lamme stated: "The broad statement may be made that it is no more difficult to commutate an alternating current than an equal direct current."

Obviously, if the flux per pole be kept to a sufficiently low value, it is possible to obtain black commutation.

The recent advances in the art which permit a close approach to the desired value of low flux per pole are:

1. Increased peripheral speed of commutator.
2. Increased peripheral speed of armature.
3. Increased number of armature ampere turns per inch of armature diameter.
4. Use of anti-friction bearings.
5. Development of suitable auxiliary and control apparatus.

Increased peripheral speed of commutator has permitted a larger commutator diameter for any given rev. per min. as well as an increased number of bars per commutator. The increase in diameter of commutator together with improvements in detail of construction has permitted the placing of more brush holders around the commutator.

The increased number of bars per commutator, together with improvements in mechanical structure and in insulation, has permitted a greater number of conductors per armature.

The increased peripheral speed of armature obviously obtains a given horse power with less torque at the air gap.

The increase in armature ampere turns, both from increase in conductors and in amperes per sq. in., permits a decrease in total flux required for any given horse power.

The use of anti-friction bearings insures uniformity in air gap.

A uniform air gap lessens losses and duty on the cross equalization. This also insures more uniform current balance in the main and interpole field coils and hence improves the rating of the stator.

With the increase in number of poles of any given motor the external amperes input to the motor increases since the current per brush arm is maintained at the same value.

It is of interest to note that some twenty years ago Mr. R. E. Hellmund developed and tested, a low flux motor for multiple unit car service. This motor was not considered commercial at that time because the unit switches, reversers, etc., available and required for the external current involved, were objectionably large for car mounting.

During recent years the intensive development program warranted by important electrification prospects has secured the reduction of flux per pole to the permissible economical value obtainable with present developed limits of over-all design of both motors and control.

The paper of Mr. H. G. Jungk, printed on page 278, forms an interesting contribution to this whole subject.

The pioneer motor which has stimulated this development was constructed of full capacity about three years ago and was demonstrated to interested parties shortly thereafter and led to the construction of the high-speed locomotives which are now in operation.

The operating results have been most successful and some 20,000 miles service has already been reached.

A Cooperative Electrolysis Survey in Louisville, Kentucky

BY W. C. WHITE[1]

Non-member

Synopsis.—A cooperative electrolysis survey in the city of Louisville, Kentucky, under the direction of an electrolysis committee is described. An analysis of a portion of the survey data and indicated mitigation measures are given as typical examples. The advantages of cooperative action in a general electrolysis survey are shown.

INTRODUCTORY

THE electrolysis problem has existed in the city of Louisville probably as long as in any other city of the United States since Louisville was the third city in which street railways were electrically operated. Up to 1926, the method of attack had been largely upon the basis of individual action, by each utility owning underground metallic structures, in an attempt to mitigate specific cases of electrolysis hazard. While these had resulted in generally satisfactory conditions of the underground cable plants, they had not been as successful with respect to water and gas pipes. The absence of complete electrolysis data covering the city of Louisville augmented the difficulty of reducing the hazard to the latter structures.

It was realized that the best engineering solution of the electrolysis problem as affecting all utilities could be obtained only upon the basis of very complete data covering the electrolysis condition of the affected structures and detailed information concerning the railway system, including those characteristics of the system affecting the magnitude and direction of stray return current. It was for these reasons that the Gas and Electric Company suggested a conference of all interested utilities to consider the desirability and practicability of cooperative action in the making of a comprehensive study of the Louisville electrolysis situation and determining suitable measures for improving conditions generally. Such a meeting was held early in 1926 and attended by representatives of all interested utilities including the City Water Department, the Railway Company and the Louisville Public Utilities Bureau.

The outcome of this conference was the formation of the Louisville Electrolysis Committee consisting of executives representing each interested utility with the chief engineer of the Louisville Public Utilities Bureau as chairman. This committee appointed a working or technical committee of engineers representing each utility and included a consulting electrolysis engineer retained by the Gas and Electric Company. The expense of the investigation was prorated among the interested utilities through the furnishing by each utility of its prorata share of engineering, labor, tools, meters, circuits, and materials as agreed upon by the general committee. This obviated the necessity for special accounting and inter-billing among the various utilities.

The technical committee prepared an outline of a proposed test procedure which was endorsed by the general committee and steps were taken to put it into operation. The first item in the outline of test procedure called for a general check up of the various underground structures by the individual utilities in order to correct so far as possible all obviously undesirable or abnormal electrolysis conditions. This check up included on the part of the railway company a comprehensive track bond test of their entire system and the repair of all bonds found defective; on the part of the cable owning companies investigations to make certain that all cables were properly cross bonded, that electrical drainage connections were in satisfactory operating condition and that there were no undesirable metallic contacts to other underground structures; on the part of the pipe owning utilities investigation of all known or suspected electrical drainage connections to determine which of these connections were in effective operating condition.

When the above work was completed, the technical committee started the field work of the general survey, which in general comprised a potential survey, a current survey, over-all track drops and gradients, and soil resistivity tests.

POTENTIAL SURVEY

A potential survey was made of the entire city, tests being made at more than 600 locations.

It is desired to emphasize the importance of a potential survey in the investigation of an electrolysis problem. The potential survey is the qualitative indication of the condition of the various sub-surface structures at the point and at the time tests are made. Therefore, for all data to be comparable, tests, in general, should be made under normal street railway load conditions, and the potential relations of the various structures at each test location measured simultaneously. The potential readings may be taken either with indicating or recording instruments. In the Louisville investigation, due to both the number of structures involved at each test location and to the large area to be surveyed, it was

1. Southern Bell Tel. & Tel. Company, Atlanta, Georgia.

Presented at the Southern District Meeting No. 4, of the A. I. E. E., Louisville, Kentucky, November 19-22, 1930.

found advantageous to use recording instruments. Twelve recording meters of the smoked chart type were mounted on a truck and suitable switching arrangements provided for connecting these by flexible insulated conductors between various structures and between structures and earth (See Fig. 1). To assure that connections to the various structures were of low resistance, provision was made for testing such connections with indicating meters and batteries. Six-hour clock movements were used. As the period of test at each location was approximately 20 minutes, this permitted a full day's test of each particular structure at approximately 10 locations to be recorded on a single chart.

Test locations were selected approximately 1,000 ft. apart in the outlying areas and approximately 500 ft. apart in the more congested areas, or in areas of positive-to-rail potentials in the case of piping systems

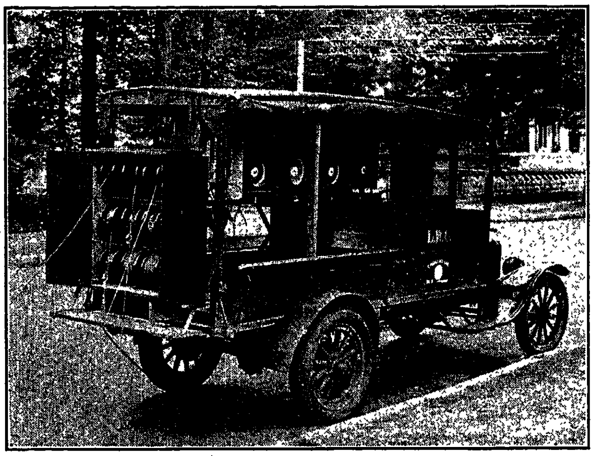

Fig. 1—Typical Truck Equipped for Use in Cooperative Electrolysis Survey

and positive-to-earth potentials in case of cable systems.

The criterion of electrolysis hazard to metallic sub-surface structures is the potential thereof to immediately adjacent earth. The best practical approximation of this in the case of lead sheathed cables is the measurement of potentials to earth via the bottom of a manhole or an adjacent spare duct. In the case of pipe systems, due to the fact that they are in such intimate contact with the earth, that these values are relatively small and due to the usual inaccessibility of adjacent earth, the best practical index is the potential to trolley rail and other nearby structures.

At each location, records were made of potential differences between all structures and rail, between all structures and water pipes, (the water system having been selected as a reference due to its being the most extensive system), and between all cable systems and earth. It is the purpose of cable-to-rail readings to determine which structure is probably the disturbing element *in a particular location* as well as to determine the points where drainage may be most advantageously applied; for instance a cable may be positive to earth yet negative to rails, which would indicate some other structure as the disturbing element. The use of water pipes as a reference system provided for tie readings which served as a check on the reliability of all readings taken.

Current Survey

A current survey of sub-surface structures supplements the potential survey in determining probable hazardous conditions, and furnishes valuable data for consideration in the application of remedial measures.

A current survey of cable systems is a relatively simple procedure and in a great many cases will indicate hazardous conditions where they would not otherwise be located. For example, the potential survey may indicate safe conditions at the points of measurement, while the current survey may show an abrupt change in the magnitude, or even a reversal, of the current in adjacent manholes such as to indicate hazardous conditions between the two manholes.

Current surveys of pipe systems are generally difficult and expensive to conduct unless suitable test stations have been provided for this purpose, since the readings require the exposure of a suitable length of pipe usually by excavation. For this reason current test stations should be installed on pipe systems, either when maintenance work is being done on existing lines or during the installation of new lines, their proper location having been previously determined by a study of the pipe systems in conjunction with the railway system.

Approximately 72 such test stations were installed on the water and gas systems at Louisville and 24-hr. smoked chart records obtained of the current. Also in the study of the problem numerous potential drops were taken between services for determining the direction of the current.

Over-all Track Potential Drops and Track Potential Gradients

The magnitude of stray currents, in general, depends upon the magnitude of over-all track potential drops and track potential gradients. High over-all track potential drops and track potential gradients result from long feeding distances with inadequate return circuit conductivity and heavy concentration of return current in the rails.

A large number of over-all track potential drops and track potential gradients was made on the Louisville Railway system. The over-all drops were 24-hr. records and were made from various points of the track system to the negative bus, or to the point of low potential in the case of insulated return feeder systems. The potential gradient measurements were also made with recording instruments and covered periods from 30 min. to one hr. under peak load conditions. These data are not only necessary in the study of a general electrolysis problem but are of value to the railway

engineers in the design and maintenance of their negative feeder system from the standpoint of railway economies. In the design of a feeder system, the peak load conditions are in general the determining factors.

The obtaining of over-all track potential drop data would generally be difficult other than in a cooperative investigation where the telephone company can furnish spare cable pairs to various locations to serve as voltmeter leads. These leads, of course, should be tested each time use is made of them to insure reliable results.

Soil Resistivity Tests

Soil resistivity tests were made of some 180 samples and while there was a wide range in the resistance of some samples, it was found that for the most part the soil averaged about 5,000 ohm cm. In general this would not be considered a high resistance soil and from the fairly consistent results obtained it would appear that the potential measurements gave directly a fair indication of relative stray current interchange between affected structures and that the resistance of the soil did not by itself account for the areas of high-or-low potential differences between structures.

Assembly of Test Data

At the time potential or current tests were made at selected locations, a card was prepared giving the number and location of the test point and cross referenced with the corresponding smoked chart records. On the reverse side of this card was shown a diagram of the test point and the location of structures to which connections were made. This was done in order that any test could be repeated with identical connections at any time. At the conclusion of each day's test the smoked chart records and cards were sent to the office where the data on the smoked chart records were averaged and recorded on the cards.

Those portions of the data capable of graphical presentation were plotted on suitable maps. These maps were skeleton maps of the street railway system. The water and gas pipe potentials were plotted to scale using the railway track system as a base line. The ordinates of positive potentials were shown to the north and east of tracks and negative potentials to the south and west These ordinates were then connected with straight lines and the positive areas colored red and the negative areas blue. The cable data were plotted in a like manner using, however, duct runs as base lines and plotting the potentials of cables to rails and earth. Over-all track potential drops and gradients were also shown on the maps but the actual numerical values were used.

This manner of presenting data is of advantage, especially in a cooperative study, as it furnishes a composite picture of conditions and assists in determining the disturbing element in any particular location.

Analysis of Data and Mitigative Measures

The technical committee arranged to meet once each week during the field survey, for the purpose of considering the data as they were obtained and to interchange information as to the operation or rearrangements of any plants which might affect the electrolysis situation.

When sufficient data were obtained in any section from which definite conclusions could be reached, mitigative measures were recommended in order that these might be applied as the survey progressed.

While it will not be possible to go into the details of this phase of the work some of the more important points considered in the analysis of data and in the application of remedial measures may be mentioned.

From various data obtained such as track drops and gradients, drainage currents, and potential readings it was found that a very considerable improvement in the electrolysis conditions could be made by beginning the operation of the Number 3 substation of the railway

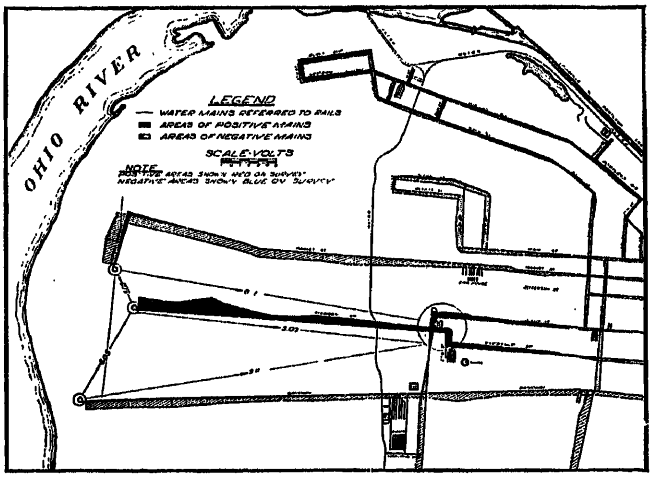

Fig. 2—Illustration of Graphical Presentation of Data

company, one hour earlier in the morning and continuing its operation until one hour later in the evening, and by operating the Number 2 substation for a 24 hr. period instead of part time. This recommendation was carried into effect.

From a study of the track drops and gradients it was felt that some of these were excessive. Additional substations, with the resultant shortening of feeding areas, were recommended as a means for reducing the high over-all track drops and these are now being considered.

Even where over-all track potentials are not of themselves excessive, unequal drops on long paralleling or approximately paralleling lines may produce hazardous electrolysis conditions. This is illustrated by the following case which also shows the necessity for complete reliable data in the solution of the problem.

In the Number 3 substation area there are three long

paralleling lines, *viz.:* the Broadway, Madison and Market Street lines, with no cross lines for interconnection. The potential survey showed that positive pipe-to-rail potentials existed throughout the length of the Madison Street line, which was the center line. The over-all track drops to the Number 3 substation negative bus were approximately 9, 3, and 8 volts respectively from Broadway, Madison and Market Streets (see Fig. 2). The Broadway and Market Street Lines were of older construction and heavily loaded while the Madison line was of new welded rails and lightly loaded. It was therefore evident that the positive potentials were due to shunting currents from the Broadway and Market lines to the lower potential line on Madison Street. The method which was recommended and carried out for correcting this condition provided for additional negative feeders to the Broadway and Market lines, insulating the negative bus in the Number 3 substation and installing resistance grids in the short feeder attached to rails near the junction of the Madison Street line.

These positive conditions upon the pipes had been known for a number of years but the absence of sufficient data made the engineering solution difficult.

Considerable positive cable-to-earth potentials in the downtown section were eliminated by equalizing potentials through fused interconnections of the cable systems. The railway cables were found to be heavily drained and it was recommended that these be brought nearer earth potential by limiting the drainage currents. At one point it was found that more than 100 amperes was being drained from the power cables and that the telephone cables also required drainage at that point. Upon recommendation of the technical committee these two cable systems were interconnected and it was then found that a drainage current of approximately 35 amperes was sufficient to maintain both systems at a satisfactory negative potential to earth.

While reduction of stray current is of primary importance in mitigating electrolysis hazard to underground structures, cable systems usually require, as a supplementary measure, the application of a certain amount of drainage for the reason that the corrosive action on lead is rapid and the sheath relatively thin. Fortunately a cable system lends itself very readily to drainage due to the continuity and good conductivity of the sheath. In general, cable drainage should be so designed as to keep the cable system slightly negative to earth.

It has generally been found that electrical drainage is only a partially effective measure in the protection of pipe systems. With pipe systems a more satisfactory supplementary measure, to the limitation of stray current in the earth, is the reduction of pipe system conductivity by the installation of insulating or high resistance joints. While there may be some isolated cases where drainage would be beneficial, pipe drainage should be resorted to only after careful study and the installation should be so made as to be readily accessible for test purposes.

Conclusion

In conclusion, it is worthy of note that in the conduct of the general survey, of subsequent special tests, and of all the work undertaken by the Technical Committee, the active interest and cooperation of the represented utilities were continuously in evidence. In a large measure the results attained and the work accomplished were due to this interest and cooperation. Realizing that it would be a serious loss to the cooperating utilities individually, and collectively if the benefits gained through this cooperation were allowed to lapse, the Technical Committee has continued in active existence and functions as a central clearing house for the investigation of all matters relating to electrolysis in the city of Louisville.

Electric Power in the Lumber Industry

BY A. H. ONSTAD*
Non-member

Synopsis.*—In the preparation of this article an attempt has been made to show the development or growth of the use of electric power transmission in the lumber industry. More particularly in that branch of the industry that is engaged in falling trees, hauling them to the mill and sawing these trees into lumber units of the size used by builders and manufacturers of finished articles in which wood is the raw material.*

An attempt has been made to show the general scope to which electricity is used, without including any technical descriptions of individual applications. It was felt that this can be best accomplished by a general description of its use throughout one of the most recently constructed and most modern manufacturing units in the Pacific Northwest.

* * * * *

THE advantages of the use of electric power transmission and electric drive in the lumber industry are many. Fuel economy, however, has not, until very recently, been counted with the advantages.

When considered, only from the angle of fuel economy, electric power had no advantage, except in a few isolated instances, over any other power as applied to the lumber industry until within the last decade. The raw material of the lumber industry, namely trees, is one of the earliest fuels used, and is still used as such in large quantities outside of the lumber industry.

The lumber industry has such an over abundance of this fuel that when cutting the trees into logs, preparatory to hauling them to the mill, the logger is very careful not to send to the mill logs that will not produce a high percentage of merchantable lumber. The sawdust produced in sawing boards is usually enough for all power needs. Any additional wood waste must be burned in refuse burners which are expensive to build and maintain and which usually scatter partly burned particles of wood over a great area with many attendant evils.

It would be hard to say when electricity was first used in the lumber industry. The writer recalls "shooting trouble" on an Edison belted bi-polar machine, which was connected to its load through a switchboard having the switches and such instruments as there were, mounted on a wooden panel, having an elaborate molded trim which would be a credit to any cabinet maker or furniture maker. When installed, this equipment was the last word in electrical equipment.

The advantages of the use of electricity for the distribution of power around a lumber manufacturing plant, aside from that of fuel economy, was early recognized and its use for this purpose began about twenty-five years ago. Prior to the adoption of electric power transmission a lumber plant had two or more complete power plants each with its complement of boilers, engines, pumps, etc., and a full operating force. One for the sawmill, one for the planing mill and sometimes one for the box factory or other side line or power user that could not be reached by belt or rope drive from the sawmill power plant.

The development of the low pressure and mixed pressure turbo generators stimulated the adoption of electric power distribution. By installing a mixed pressure turbo generator in the sawmill power house, arranging it to take the exhaust steam from the sawmill engine which was usually a Corliss engine and all the steam from the many steam cylinders in the mill, enough power could be generated to run the planing mill and other departments without drawing on the boilers for very much live steam. The cost of the installation of the generating equipment, plus the cost of the electric drives in the planing mill frequently exceeded the cost of a separate power plant for the planing mill, but the investment was justified by the reduction of the operating force and maintenance costs.

Many of the early applications of electric drive, or uses of electric power in the lumber industry that are still in use, would be hard to justify as being improvements of older and different methods. However, considering the equipment the designers and builders had to work with, the lumber industry rates as well as any other industry in this respect.

The multitudinous advantages of electricity for the distribution of power is now so fully recognized that it is accepted without question as the most economical method.

Changes being made in the method of lumber milling are steadily increasing the kilowatt hour consumption per unit of lumber, reaching as much as 121 kw-hr. per 1,000 ft. board measure in some mills that carry the manufacture to a fine degree. This change is also increasing the demand for process steam.

These changes, along with the possibility of selling all surplus power to public utility companies, or other power consumers, are placing a higher value on the mill refuse so that instead of surplus mill refuse being a liability it now has monetary value at many plants.

With such a contract for the sale of surplus power the mill company can run its generating equipment at nearly 100 per cent load factor, and if it has sufficient power plant equipment it can turn all its waste fuel (mill waste) into revenue.

This has made it imperative that efficient power

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*Weyerhaeuser Timber Company, Tacoma, Wash.

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plant equipment be installed for the conversion of fuel into power. Also that the motor applications are made with a view to conservation of power as well as continuity of service.

An example of this is the recently completed plant of the Weyerhaeuser Timber Company at Longview, Washington.

The generating equipment at this plant consists of two 7,500-kw., 80 per cent power-factor, 2,300-volt, three-phase, 60-cycle, turbo generators. These turbines operate from steam at 300-lb. gage per sq. in. at the throttle; superheated to 580 deg. fahr. When operating at full speed load 150,000 lb. of steam per hr. at a pressure of 125 lb. gage, may be bled from each machine. This bled steam is used in the heating coils of the lumber drying kilns.

Two 500-kw., 250-volt, d-c. generators driven by synchronous motors supply current for 27 cranes used for handling lumber, as well as direct current for other d-c. motors and for the exciting current for the synchronous motors.

In use at the present time are 1,200 motors, not including motor-driven tools, such as portable drills and grinders, motor-driven electrical welding sets, electrical-driven clocks, and motor-driven office appliances. These 1,200 motors aggregate 23,849 hp.

The motors are divided as follows:

71,	2200-volt synchronous motors... total	10,645 hp.
30,	2300-volt induction motors...... total	2,875 hp.
1021,	550-volt induction motors...... total	8,575 hp.
78,	220-volt direct current motors.. total	1,754 hp.

The load on this power plant with its 23,849 hp. averages 7,000 kilowatts. By the use of synchronous motors as here applied the power factor of the load is 96 per cent leading.

Electric power is now being used advantageously in every branch of the lumber industry. It is being used in the woods in a limited way for driving portable saws for falling trees and bucking them into log lengths. These saws consist of chains, with cutter teeth attached to one side of the links. These run over two sprockets, one mounted at each end of a light steel frame that serves to hold the sprockets in position and forms a guide for the saw chain. An especially designed motor of about five horsepower capacity, geared to the driver sprocket furnishes the power for driving the saw. Power for the operation of these saws is taken from nearby transmission lines, or from small gas-driven generator sets, which may be used for supplying power to several such saws working within a limited area.

Electric power is being used in a limited way for "yarding and loading" logs. This is the operation of dragging the log from where it was cut out of the tree and loading it aboard the cars for shipment to the mill.

The equipment in use varies for various sections or growth of timber. On the Pacific Slope of the Cascade Mountains, (the area where this equipment is used to the greater extent) the equipment resembles heavy duty hoisting equipment, both in mechanical construction and load characteristics.

The yarder is that part of the equipment that is used for dragging the log from the point where it has been cut out of the tree to the railroad siding for loading onto cars. Two full load line speeds are provided. A high speed being 1,800 ft. per min. and the low speed being 900 ft. per min. The higher speed is used on the smaller logs, and the lower speed used for the heavier logs. This variation of speed is obtained through reduction gears of different ratios connected to the drum by friction clutches. The usual equipment is a 300-hp. wound rotor type motor having a wide range of speed control through secondary resistance. These motors are designed for a pull out torque of approximately 300 per cent. The service is such that these motors are frequently loaded to the stalling point.

The loading end of this logging equipment usually consists of two, 75- or 100-hp. wound rotor type motors. The hoisting line of the loading equipment passes through sheaves properly supported over the load. The usual procedure in loading a log is to fasten one hoisting line at each end of one log; the log can then be manipulated through these double hoists so that the one end may be lowered onto the car ahead of the other, to conform to the requirements of binding the logs into the load in such a way that they will safely arrive at their destination at the mill pond.

For a large operation, on which load factor or days of operation per year is high, and in which life of operation is long enough to permit of reasonable obsolescence charges, this has proven profitable.

One serious disadvantage to the use of electrical equipment for woods operation, however, is the danger of loss of equipment by fire. The cost of electrical logging equipment is so great that the units are only built on order. The time required to replace a machine or repair one damaged by fire would be so great as to result in too severe a loss of production to warrant the adoption of electric power for logging operations except in a few special cases.

While the loss by fire is insurable, as far as property damage is concerned, it would hardly be practical to carry "use and occupancy" coverage on account of the cost of such coverage.

Electric power for the propulsion of the trains hauling the logs out of the woods is being used in one or two instances. Insufficient tonnage on the average logging railroad will prevent its general adoption for this purpose. The load center of a logging operation is anywhere from 15 to 30 miles from the center of the mill. The average number of trains over this main line section of a logging railway would probably be three trains each way per day. The branch lines radiating into the woods from this main line railway are seldom in service over a period of more than six months. In the case of the main line, electrification of the road would represent a large investment in the electrical

installation for comparatively few trains. For the branch lines this same electrification investment would be necessary and on account of the short period of service of these branch lines, electrification would not be economical.

There is no specific rule governing the application of motor drive to sawmill machinery. The power required for driving the various sections can be computed using the same laws that govern the application of electric drive to any other line of machinery.

Before attempting to compute the motor requirements for these applications, however, one making these computations should be thoroughly familiar with the possible loading of the various sections to be driven. In applying motor drive to live rolls and transfer chains the matter of obtaining sufficient starting torque is usually the prime consideration. The length of the roll trains and transfer tables is so short that if they are left in operation for a period of a minute or two they will completely unload all of the material that is on them.

Full voltage across the line starters is used for all motors, except wound rotor type and direct current motors.

Selecting the proper starting equipment requires considerable thought for with the frequent starting and stopping of the various sections the duties imposed on the starting equipment is even more severe than that imposed on the motors. Maintenance men spend more time keeping the starting equipment in good operating condition than they do the motors themselves.

There are many applications where thermo type overload relays will not function if the doors of the cabinets enclosing the starting panels are left closed. This is due to the rise in temperature within the cabinets caused by the arc created in opening the circuit of the motor. Some of the transfer tables in the mill are started on an average of four to five times per minute.

One of the advantages of motor drive is the ease with which the machinery can be started and stopped, which permits running the machinery only through the period that it is actually engaged in moving lumber. As this in many cases is only a small fraction of the total working time of the shifts, considerable wear and tear of the machinery is prevented by stopping its movement when not actually needed.

Among recent applications of starting equipment that has proven worth while is the automatic starting and stopping trains of live rolls and transfer chains to permit the movement of lumber over them. For instance a train of several sections of live rolls may be used for carrying timbers to the timber dock. As these timbers do not come with any degree of regularity the rolls need operate only a small portion of the time, with a trip pan arrangement placed between successive rolls throughout the length of the route. These trip pans are mechanically connected to the starting stations of the motors driving the sections, in such a manner that when the pan is depressed by the timber going over it, the motor is started and is kept in operation until all of the pans in that train of rolls are free to raise to the up position. With such an arrangement each section of rolls is started as the timber approaches the rolls and automatically stops when the timber has gone over the section.

Adapting individual motor drive to the machinery of a lumber plant presented many perplexing problems. With few exceptions, the speed of the final drive of sawmill and wood working machinery can be placed in two groups; a slow-speed group and a high-speed group.

Log hauls, transfer tables and conveyors belong to the slow-speed group, with final speeds, ranging from 1½ to 25 rev. per min. Live rolls drives ranging from 100 to 175 rev. per min. can also be placed in this class.

It was not until the so-called herringbone type gear was developed and it became practical to build speed reducing power transmissions of large reduction ratios that individual motor drive for these slow-speed groups became practical and economical. Now reduction ratios of 150 to 1 with high efficiency may be obtained. This permits the use of motors of 1,200 to 1,800 rev. per min. to be used for practically every slow-speed drive, resulting in better electrical load characteristics and greater economy of installation.

The standard ratios for gear reduction units in use by the Weyerhaeuser Timber Company are in multiples of ten; *i. e.*, units having ratios of 10 to 1, 20 to 1, 40 to 1, 60 to 1, 80 to 1, 90 to 1 and 120 to 1 seem to fit all our needs. A further refinement of speed adjustment being in the chain drive from the reduction unit to the driven machine. Steel roller chain of numbers 6, 7, 8 and 10, with double 8 and double 10, being used for extra heavy drives, are used for these final connections.

The cutting speed for the teeth of saws and the knife type cutters of wood working machines range from 8,000 to 14,000 ft. per min., which calls for speeds ranging from 300 to 7,200 rev. per min. These can be classed as high-speed drives.

The mechanical connection between these and motors of economical speed characteristics did not present the difficult problems involved in the slow-speed drives.

Recent developments in planing mill machinery such as matchers, molders, and saws, have opened a new field for the use of high-speed direct-connected motors. A large modern matcher has eight motors, totaling 270 hp., built into the machine. For these applications the machine manufacturers buy the rotor without a shaft, and the stator without a frame, and incorporate these in the construction of the machines.

It might be interesting to know that the modern

matcher (commonly called a planer) has the following motors, placed as follows:

Top cylinder...........	Two, 40-hp., 3600-rev. per min. motors
Bottom cylinder........	One, 40-hp., 3600-rev. per min. motor
Outside side head.......	One, 30-hp., 3600-rev. per min. motor
Inside side head........	One, 25-hp., 3600-rev. per min. motor
Top profiler...........	One, 30-hp., 3600-rev. per min. motor
Bottom profiler.........	One, 25-hp., 3600-rev. per min. motor
Feed work.............	One, 40-hp., 1200-rev. per min. motor

As the cutter head cylinders all turn in ball bearings and are very carefully balanced and heavy, they will continue to run for 10 or 15 minutes after the current has been cut off the motors. To make it possible to stop these quickly the control is equipped for plugging service so that when it is necessary to stop a head or cylinder for any purpose the motor is plugged, bringing it to a stop in a few seconds.

Modern molders are built for variable speeds of the spindle. This variable speed is obtained by varying the frequency of the circuit by the use of frequency changes. For normal work the cylinders are equipped with six or eight knife cutters and usually operate at 3,450 rev. per min. For the exposed surfaces of the molding that require a finer finish the particular heads being used for this exposed surface are speeded up by changing the frequency to 6,000 or 7,200 rev. per min. The control equipment is so arranged that the speed of any one or all of the five cutter heads or cylinders of the molder may be increased.

Two types of loads are selected for synchronous motor drive. First; widely fluctuating loads having a low-load factor, such as bandmills, edgers, slasher, trimmers, and hogs: Second; large loads of high-load factors such as fans, pumps, and air compressors.

Synchronous motors are not used on drives that require frequent starting.

The synchronous motors range in size from 50 to 400 hp. and in speed from 225 to 1800 rev. per min.

All synchronous motors are wound for 80 per cent power factor and have a pull-in torque of 100 per cent of full load torque. All synchronous motors are started with automatic, full voltage, across the line starters and with few exceptions are all excited from the 250-volt buses or feeders that supply power to the cranes and direct motors throughout the plant.

Synchronous motors located so far from the d-c. lines that the cost of a d-c. circuit to the motor for excitation would cost nearly as much as an exciter, are equipped with direct-connected exciters.

Synchronous motors have proven very satisfactory for widely fluctuating loads. The application to driving hogs being a striking example. Motors of 250 hp. at 600 and 720 rev. per min. and 400 hp. at 600 rev. per min. are used for this. These motors have the field control relays so adjusted that when the motor pulls out of step due to overload, the field excitation is cut out, and will automatically be restored when the motor again approaches synchronous speed. This may occur as many as 100 times during an 8-hr. shift.

The 2,300-volt induction motors range in size from 50 to 250 hp. These are mostly wound rotor type motors driving machinery requiring frequent starting, or machinery which will not permit of the severe strains imposed on it by the full voltage across the line starting. Some equipment requires limited speed control and for this purpose the wound rotor motor with drum type controllers is also used.

Induction motors of 50 hp., and smaller ratings are wound for 550 volts.

Except in sizes of 7½ hp. and smaller, the 550-volt induction motors are of the so-called double wound rotor type. These have the starting characteristics of the high-resistance rotor motor and the running characteristics of the squirrel-cage type motors.

One unusual motor application in this mill is that employed for driving the main bandsaw in the mill. For the regular run of fir logs a saw speed of 10,500 ft. per min. is the ideal speed. For a certain species fir log, one of exceptionally dense growth or one that has been dead for such a long period as to cause the wood to partially dry out, or for the logs that are frozen, such as occurs during the winter months, a saw speed of 8,000 ft. per min. is the most practical speed at which to run the saws. As these logs that require the slow-speed saws for sawing are mixed promiscuously with the softer texture logs, the custom has been to saw them all with the higher speed saw which has resulted in erratic sawing of the hard or frozen logs. At this Longview mill we arranged for practically instantaneous speed changes from 10,500 to a speed of 8,400 ft. per min. This was accomplished by putting two synchronous motors on one motor base, with the shafts rigidly coupled together, driving the same pulley. A 400-hp. 600-rev. per min. motor was installed as the main motor to use in starting the bandmill and for sawing the average run of logs. The other motor was a 250-hp. 450-rev. per min. motor. While the large motor is used for furnishing the power the small motor is disconnected from the line so that the only power required to drive it is that necessary to overcome the windage losses. When a hard log is sawn the sawyer, by pressing two push buttons, disconnects the large motor from the line and connects the small motor, which drops the speed of the saw to 8,400 ft. per min. The change from one speed to the other being made as frequent as the sawyer deems it necessary to make the changes.

Another unusual application of electric power to sawmill machinery is in driving the feed works of the larger edgers. The edger is the machine that rips the boards and timbers into the desired widths. The edger arbor on which the saws are mounted is direct-connected to a 400-hp. 80 per cent power-factor, 1200-rev. per min. synchronous motor. The feed rolls that feed the stock into the edger are driven by a 10-hp. series wound motor through reduction gears and chain drive. These are so proportioned that with no load on the motors the surface speed of the rolls will pull the lumber into

the edger as rapidly as good work can be done with the saws. As larger and thicker pieces are sent through the edger the load on the feed works motor increases and automatically decreases the feed so that the thicker stock is fed into the edger more slowly. The speed characteristic of the 10-hp. motor is such as to automatically provide the proper rate of feed into the saws for the varying thickness of material being sawn.

Another application of electric current is by the use of solenoids for remote operation of cylinder valves. By use of solenoids for this purpose the valves of cylinders can be operated from several distant points.

Among unusual applications of electric power to sawmill machinery is that used by the Weyerhaeuser Timber Company at their Mill "C" Everett, Washington. This mill is located approximately three-quarters of a mile away from the power plant. The mill is equipped with individual motor drive throughout but differs from the usual mill in the respect that no steam is used in the mill for any purpose. This mill is so far from the power plant that the cost of a well constructed steam line was such that it was decided to use compressed air in place of steam for operating all lifting cylinders, loaders, niggers, etc.

A two stage air compressor having a capacity of 1,500 cu. ft. of free air per min., driven by a 250-hp. synchronous motor furnishes all of this compressed air.

For driving the sawmill carriage a slow speed d-c. traction type elevator motor was used. This motor differs from the elevator motors in that it is not rated in horsepower The specifications for the motor called for a torque of 12,500 lb. rather than the conventional horsepower rating. Power for this motor is taken from a motor-generator set consisting of a 75-hp., three-phase motor driving two d-c. generators; one for furnishing current to the armature of the motor and a smaller one for furnishing the current for exciting the fields of the generator and the motor.

The armature leads of the motor are directly connected to the armature terminals of the generator. Full field is left on the motor at all times. The speed of the motor is controlled by varying the voltage of the generator through field resistance placed in the field circuit of the generator. Reversal of the motor is effected by reversing the fields of the generator.

This motor is connected to the carriage through wire ropes, one end of which is securely fastened to the carriage; the other end being fastened to a 30-in. diameter sheave on the motor shaft.

The cycle of operation of this unit is two revolutions in one direction and then two revolutions in the opposite direction. Under normal operation this unit makes from seven to thirteen cycles per min.

Owing to the lack of ventilation, because the motor does not set up any windage through the coils by its own revolutions, it was necessary to provide artificial ventilation. This was accomplished by enclosing the motor in a galvanized iron housing and forcing cool air through this housing by the use of a motor-driven fan.

Accurate and quick speed control of a sawmill carriage is absolutely essential. The method used in the control of this drive, which is the Ward Leonard System, has proven highly satisfactory in every respect.

The newest use to which electricity has been placed in the sawmill industry is that of the Taglibue-Heppenstal moisture indicator. This consists of a case in which is mounted a battery, some amplifying tubes and transformers and an ammeter. Long flexible leads from this cabinet are connected to two sharp terminals in a small portable handle that the lumber tester carries with him when inspecting lumber.

By driving the steel terminal points that are on the handle into the wood, a current is set up in the circuit, the amount being governed by the moisture content of the wood. The value of this current is calibrated as percentage moisture content of the wood.

This method of testing for "dryness of lumber" has proven so dependable that it is now a standard for testing lumber that is bought on a specification calling for a definite moisture content.

Storage battery locomotives usually of seven ton capacity having 225-ampere hr. batteries are used for the transportation of lumber from one department to another, where these departments are so arranged that transportation cannot be readily accomplished by crane service. These locomotives run on a 30-in. gage track pulling four wheel industrial cars equipped with roller bearings. As the tracks are in good alinement and the grades are practically eliminated, one locomotive will haul a train of 15 cars or 60 tons on one charge of the battery and stay in service an 8-hr. shift without recharging the battery.

Small storage battery trucks and lift trucks are used in some departments for stacking certain items of lumber and for short distance movement of lumber.

With modern industrial lighting units it is possible to provide illumination so suited to the work that production can be carried on at night with as high a rate of efficiency as that obtained during daylight operation.

Progress in the Design of the Single-Phase Series Motor

BY H. G. JUNGK[1]

Associate, A. I. E. E.

Synopsis.—The paper deals with the development of the design of the single-phase series motor and some of the main features in both electrical and mechanical proportions which determine the service capacity in the application of this type of motor to railway electrification.

Intensive study and development begun in the early part of 1927 resulted in the production of a singe-phase series motor with more than enough capacity to meet the present day requirements of the American railroads. A brief description is given of this motor and of some of the novel features which made this recent progress possible. Since this motor was developed, built and tested, further possibilities of increasing rating or decreasing the size and weight for the same rating have been found and will result in further progress in the design of the single-phase series motor.

THE single-phase series motor for 25 cycles has been developed to the stage where it fulfills the present day railroad requirements, that is, high horse-powers per axle at high speeds. A high-speed passenger locomotive equipped with single-phase series motors with shunted interpole developed and built by the Westinghouse Electric & Manufacturing Co. has been operating since July, 1930. The continuous rating is

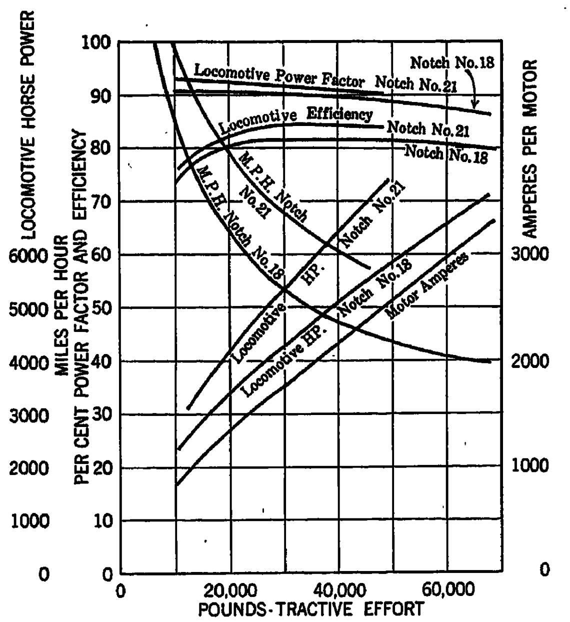

FIG. 1—PERFORMANCE CURVE OF PASSENGER LOCOMOTIVE EQUIPPED WITH FOUR No. 422-A SINGLE-PHASE COMMUTATOR MOTORS

Includes input to all auxiliary apparatus and gearing

more than 1,000 hp. per axle at 56 mi. per hr. In service the locomotive has exceeded the performance for which it was originally designed and has clearly demonstrated that it is now practical to build a 25-cycle single-phase locomotive for as high as 75,000 lb. axle loading geared to operate at a maximum sustained speed of 90 mi. per hr. The characteristic curves are shown in Fig. 1.

This development was started more than three years ago in spite of the fact that at the time opinions were expressed that such a design was impossible. The outstanding features which made this possible were:

a. Roller bearings.

b. Commutators and armature windings designed to operate at higher peripheral speeds than heretofore considered good practise.

c. More compact ventilating scheme.

d. Improved quality of magnetic material.

e. Rolled steel housings and welded frames.

f. The disk spring commutator.

g. Improved designs of gears, pinions and mechanical drive.

Considerable credit is to be given to the European designers and manufacturers of single-phase railway apparatus in Germany, Austria, Switzerland, and Sweden, especially to the German engineers who were the first to apply generally roller bearings to locomotive motors in order to take advantage of the higher peripheral speeds on 16⅔-cycle single-phase series motors.

Once the fact was demonstrated that such high ratings were also possible on 25-cycle single-phase series motors, a number of further improvements has been found which permit the design of motors of even larger capacity in the same space and weight. The development of the single-phase commutator motor cannot be attributed to any one manufacturing firm or group of individuals. Its development is nearly as old and as broad as that of alternating current. The purpose of this paper is to describe briefly its history and how evolution led to the present day designs.

The single-phase commutator motor, though the fact is not generally recognized, followed closely the conception of the synchronous motor which was the first a-c. motor. The original designs were patterned after the d-c. series motor. The first appearance in literature of the mention of the possibility of such a motor was in 1884 by Alexander Siemens. This was followed by the experiments and attempts of Elihu

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Thomson in 1887 with the repulsion motor. Although not entirely successful the idea was followed up and in 1892, E. Arnold brought out a more successful repulsion motor which embodied the principles of the repulsion, the doubly fed and the series motor. This led to the Wagner and to the Deri motors which were developed for industrial application on 50 cycles or higher frequencies. The difficulties of commutation on the higher frequencies at this time, together with the advent of the induction motor, pushed the a-c. series motor into the background until after 1900.

The first real impetus to a practical application of the series motor for traction purposes came in 1902 when B. G. Lamme brought forth a single-phase series motor for railway application and emphasized the importance of a low frequency, having chosen 15 cycle for his motor. Independent developments in Europe at about the same time brought out a test locomotive for the Prussian State Railways in 1903 as a result of the endeavors of Winter, Eichberg, and Latour.

The first outstanding electrification was that of the New York, New Haven and Hartford Railroad in 1907 in which Lamme and Storer designed and built resistance lead series motors which are running successfully today. The principal objectives of Lamme for this development of the series a-c. motors, notwithstanding certain limitations in design, are given as follows:

a. To make use of the outstanding advantage of the series motor for traction purposes in conjunction with the alternating current high-voltage contact system which permits the maximum concentration of power in a given section with the minimum size of conductors and supporting structure and substation capacity, as well as high transmission efficiency.

b. To obtain a motor with minimum power requirements for acceleration.

c. To obtain a motor whose tractive effort could be maintained within limits over the entire speed range by varying the voltage of the motor, irrespective of motor combinations, by change in transformer taps, thus obtaining a maximum output.

Several outstanding features resulted from this New Haven Electrification:

a. Some of the passenger locomotives were operated at speeds of over 100 mi. per hr. but at a limited capacity because the axle loading was around 40,000 lb. and gearless motors were used.

b. The individual axle drive of the flexible quill type was developed for

1. Gearless motor (No. 130 motor).
2. Geared single motor (No. 403 motor).
3. Geared twin motor (No. 409 motor).

The gear twin motor with flexible quill drive has made it possible to design for considerably more horsepower per axle with smaller high-speed motors and narrow gear face.

c. Single-phase multiple unit cars.

Considerable independent development took place in Europe at this time. The work of Dr. Behn Eschenberg, R. Richter, and M. Latour produced the series motor with the compensating winding and series interpole shunted by resistance. The limitations of short-circuit currents in coils undergoing commutation were investigated and the combination of a brush, two bar pitches wide with a limit of 7 volts from one tip to the other was established, limiting the maximum flux per pole at start to

1.6 megalines at 50 cycles.
3.2 megalines at 25 cycles.
5.3 megalines at 15 cycles.

Dr. Behn Eschenberg in 1908 had investigated telephone disturbances caused by armature slots and recommended that the slots be skewed to minimize this effect. These general limits of electrical design characterize the designs of today.

The first experimental series motor with interpoles which the Westinghouse Electric & Manufacturing Co. built was in 1911. This motor had low flux per pole and interpoles shunted with resistance. Mr. Hellmund, in his tests with this motor, found most of the relations which characterize the designs of today but could not take full advantage of them at that time because both switches and reversers were then too big and heavy to handle the larger currents economically.

The doubly fed motor with repulsion start worked out better with the available control apparatus and this type of motor was applied to multiple unit cars. Considerable development of the doubly fed motor took place in which Arnold, Richter, Hellmund, Alexanderson, Punga, Latour and others did considerable to advance the art. The original and major number of motors used on multiple unit cars of the Pennsylvania Railroad at Paoli are of the doubly fed type, and the armatures of these motors were the first to be wound with the split-throw[2] or fractional-pitch windings to improve commutation.

The World War retarded progress a second time—more in Europe than in America of course—and it was not until 1919-20 that a multiple-unit car equipped with a single-phase series motor with resistance shunted interpoles was tried out in service on the Paoli line at Philadelphia. Weakening of the exciting field at start was tried on this equipment by connecting the fields of two motors in parallel at start and then changing to fields in series for the running connection. A second trial equipment in 1924 was tried in service with the field shunted by a reactor to reduce the field strength at start. This motor is still operating satisfactorily in daily service.

In 1923-24 a large locomotive motor of the single-phase series type with shunted interpole was designed

2. Patent No. 1298705, R. E. Hellmund, April 1, 1919.

and built for gear and side rod drive on the Pennsylvania Railroad.

As Europe recovered from the war considerable progress was again made in Germany, Austria, Switzerland and Sweden, where the single-phase systems were adopted as standard for electrification. The single-phase series motor with shunted interpole was generally applied with a definite trend toward individual axle drive. The doubly fed motors and resistance-lead motors were set aside. The necessity for smaller motors with greater capacity brought on an intensive development, both in drive and in mechanical construction. Attempts were also made to exceed the established limits in electrical design.

In Germany, Siemens-Schuckert concentrated on Geh. Reichel's objective of a single axle-hung motor for passenger locomotives and succeeded in developing 600 hp. per axle with 44,000 lb. axle loading for a maximum speed of 62 mi. per hr. The application of roller bearings and an increase in peripheral speed of commutators to 9,000 ft. per min. were the main features which made this possible.

AEG.[3] engineers directed their efforts toward producing the Kleinow locomotive with twin motor per axle drive and succeeded in producing a locomotive with 700 hp. per axle within the limits of 44,000 lb. axle loading and 60 mi. per hr. maximum speed.

In Austria, Siemens-Schuckert produced a passenger locomotive with vertical motors and, although a novel departure in drive construction, has given good results.

Brown Boveri Co. built locomotives with their single motor per axle drive and omitted the compensating winding in the pole face but used the shunted interpole in an effort to increase the number of poles on the motor. The outstanding result of their work was to develop a compact design of brush holder so as to place the maximum number around the commutator. This was reflected in the motor built for American application where 24 holders were placed around a 48-in. commutator and later 10 holders around a 17-in. commutator.

The European designs, not being hampered with the limitations of higher frequency, had commutation constants which were quite reasonable. The recent efforts of the Europeans described above may be summarized by saying that their attempts were directed toward obtaining more motor capacity for a given weight and displacement, higher efficiency and better power factor. This was made possible fundamentally by the application of roller bearings and improved armature and commutator construction for higher speeds together with the use of more poles, resulting in more capacity per pole and more poles for the same space and weight.

The development and successful application of the roller bearing has had considerable effect on designs. Long life, less lubricant and maintenance of a uniform air gap, together with a much higher journal speed, permit a considerable increase in armature rev. per min. An armature combination designed for a given flux per pole and ampere-turns when rotated at a higher speed will of course have a proportionally higher output. Compared with older designs a higher speed armature requires less flux per pole for the same total armature ampere-turns to produce the same output. This allows us to shorten the length of core, all of which results in higher efficiency and power factor for less weight of active material. The commutator design must be improved to stand higher peripheral speeds and likewise the armature core and windings.

In 1926-27 the problems in connection with the electrification of some of the larger American trunk lines became more active. Our twenty-five years experience in a-c. electrification and our knowledge of the $16\frac{2}{3}$-cycle development in Europe gave us considerable data with which to proceed. The handicaps of 25 cycles over $16\frac{2}{3}$ cycles is of fundamental importance in motor design. Starting conditions of commutation definitely limit the flux per pole. For the same voltage between commutator bars, the 25-cycle motor can have only $\frac{2}{3}$ the flux per pole of a $16\frac{2}{3}$-cycle motor. Hence for the same torque a 25-cycle motor must have either 3/2 times the armature ampere turns or 3/2 times as many poles as a $16\frac{2}{3}$-cycle motor, or a partial increase in both armature ampere turns and poles to make up for $\frac{2}{3}$ the flux. In addition to this, the axle loading in Europe on the $16\frac{2}{3}$-cycle motors is not more than 44,000 lb. while here in America with 25 cycles, the axle loading is as much as 75,000 lb. Hence the problem here is to design for $\frac{75{,}000}{44{,}000}$ or 170 per cent of the axle loading and starting tractive effort with $\frac{2}{3}$ the flux per pole and either 3/2 the poles or 3/2 the armature ampere turns required in Europe. Besides this, the maximum locomotive speed in Europe is 62 mi. per hr. (although this may be increased to 75-80 mi. per hr.) while here in America we are designing for 90 to 100 mi. per hr. maximum. Hence with 170 per cent of the starting tractive effort per axle, 150 per cent of the maximum running speed with $\frac{2}{3}$ the flux per pole and either 3/2 the poles or 3/2 the armature ampere turns, the proportions of our motors differ somewhat from those of the European motors.

Our engineers studying the problems of electrification economies, application, etc., put before the design engineers the problem of designing and building a motor suitable for freight service as an axle-hung motor and suitable for passenger service as a twin motor with flexible quill drive with motor parts interchangeable, which entails design difficulties. Railroad limitations at the time were 60,000-65,000 lb. axle loading, 45-50 mi. per hr. maximum speed for freight and 90-100 mi. per hr. maximum speed for passenger locomotives for

3. Allgemeine Elektricitaets Gesellschaft.

operation on 25 cycles. Designs were worked up and the first test motor was built for 25 per cent adhesion at 60,000 lb. axle loading geared for 90 mi. per hr. maximum speed, with a continuous rating of 1,000 hp. per axle at the rail at 55 mi. per hr. The motor was tested early in 1928 and the fact was clearly demonstrated that such a capacity was possible with 72 in. drivers. A change in ventilation was then made with the result that a motor rating of 1,220 hp. per axle at 56 mi. per hr. could be obtained by an increase in current without exceeding A. I. E. E. temperature limits.

Following these tests twin motors were built in mechanical parts designed to mount in a locomotive. Development was then concentrated on the commutator construction and the new disk spring type was developed in which the bars are held together by the force exerted by a disk spring pressing against the vee ring. Tests on this commutator show that the limit of 9,000 ft. per min. is a conservative one, in fact as soon as sufficient service data are obtained it may be possible to go to 10,000 ft. per min. or even higher with this disk spring construction. Increase in commutator speed for a given locomotive speed will produce more service capacity for a given motor weight and displacement.

The field of the motor is shunted at start and allows the possibility of designing for maximum flux at continuous rating independent of the value necessary at start. In fact the motor has the same flux at standstill as at continuous rating with the present locomotive control scheme.

A ventilation scheme was developed to eliminate fan members on the armature in order to increase the over-all length of active parts. At the same time the arms of the spider and coil support provide an internal blower which assists in the circulating of the air through the armature passages.

To eliminate the difficulties of securing adequate cast steel frames of the size required, a new welded rolled steel frame was developed. Housings and commutator parts, also of rolled steel, were developed for the motor to take up less space because they are relatively lighter and stronger. The motor frame and housings were dimensioned and designed to take electrical parts of either 12, 14, 16, 18 or 20 poles. The original motor was designed for the minimum number of poles in order to get the maximum voltage and minimum current. This required a design wherein three commutator bars are spanned by the brush in order to get a brush of sufficient mechanical strength and smooth riding qualities on the commutator.

The motors for the existing locomotive were ready in the latter part of 1929 and the locomotive was placed in service the first week in July 1930. The actual weight on drivers is higher than the 60,000-lb. axle loading for which the motor was designed, hence the motor will be tested with more severe starting conditions than originally contemplated. The performance of the locomotive has exceeded expectations. The experience gained through the operation of this locomotive in service with the increased axle loading and the knowledge and experience gained in the past 3 years, make it possible to design for as high as 75,000 lb. axle loading at the same speeds.

In order to design these motors and take advantage of the best proportions, the major relationships of the fundamental limitations in design were comprehensively analyzed on the following basis. The required capacity of any motor applied to a locomotive or car is determined by starting tractive effort and the maximum sustained running speed at which the locomotive or car must operate. The gear ratio and wheel size must be so proportioned that the commutator speed will be within safe limits at the maximum sustained running speed of the locomotive. The maximum tractive effort which may be obtained with this gear ratio and wheel size is limited by the current carrying capacity of the brushes and commutator or armature windings. The continuous capacity is then the output at some voltage and speed with this gear ratio, wheel size and current carrying capacity at which the temperatures do not exceed certain safe values.

For multiple wound armatures:

Gross tractive effort = flux per pole × brush current density

$$\times \text{ poles} \times \frac{\text{peripheral speed commutator}}{1414 \times \text{mi. per hr.}}$$

$$\times \frac{\text{Width of brush}}{\text{Bar pitch}} \times \text{active length of commutator}$$

$$\times \cos . \alpha \times \text{gear efficiency}$$

where active length of commutator is the total length of brushes in a brush holder.

The gross tractive effort can be converted into net tractive effort at the rail by deducting rotational losses and gear losses which are of the order of 5 to 10 per cent. At standstill the cos . α may be of the order of 90 per cent but is practically unity above ¼ speed.

The limiting factors in the motor design are

1. The maximum peripheral speed of the commutator which determines both the diameter and length of the commutator.

2. The permissible current density in the brush which, for a given number of brush holders, limits the size of the brushes and the active length of the commutator but depends on the flux per pole.

3. The flux per pole which not only determines the magnetic sections of the punchings and the length of core but also the voltage between commutator bars at standstill and the circulating currents in a coil being commutated. This circulating current in turn limits the permissible current density in the brush.

4. The bar pitch of the commutator which limits the width of the brush for a given flux per pole and hence the current per brush holder.

5. The number of brush holders which can be

placed around the commutator which limits the number of poles.

The maximum peripheral speed of a commutator is a mechanical limitation. The dimensions of the individual bars and the method of holding them together determines the safe maximum speed at which the commutator may rotate without overstressing the parts. Disk spring commutators have been built to operate at 9,000 ft. per min.

The flux per pole at start, the permissible current density in the brush and the maximum number of bars spanned by a brush at any time are all very closely related and depend entirely on the characteristics of the carbon brush. The resistance of contact of any carbon decreases with temperature rise. On brushes with high contact drop, the circulating current in the coil short circuited by the brush varies about as the square of the voltage induced in the coil, reaching a critical condition between 3.5 and 3.75 volts above which the current increases very rapidly with a slight increase in voltage. Since this characteristic is caused by local heating it is evident that, with line current also carried by the brush, the voltage induced in the short-circuited coil must be held below this critical point. Tests have shown that some carbons will stand as high as 2.9 volts between bars and a load current density of 150 amperes per sq. in., where the brush is two bar pitches wide and is in contact with three bars most of the time.

If we substitute these values in the equation for tractive effort we have at 25 cycles:—

Gross tractive effort at start

$$= \frac{2.6 \times 150}{1414} \times \text{poles} \times \frac{9000}{\text{Max. mi. per hr.}} \times 2 \times$$

$$\text{active length of commutator} \times \cos . \alpha = \frac{4960 \times \text{poles}}{\text{Max. mi. per hr.}}$$

$\times$ active length of commutator $\times \cos . \alpha$.

Therefore with the tractive effort required for starting and the maximum mi. per hr. for sustained running speeds, the poles and active length of commutator may be readily determined. This brings us to the requirements of the car or locomotive.

On multiple unit cars, the weight on the driving axles will probably not exceed 40,000 lb. Since sand is seldom used the maximum adhesion will not be over 18 per cent giving a possible starting tractive effort of 7,200 lb. per axle. Geared at 70 to 75 mi. per hr. it would be possible to accelerate such a car at 1 mi. per hr. per sec. with only one axle driven by a 12-pole motor with 10 in. active commutator. With motors on two axles it would be possible to haul a trailer.

For a locomotive of 60,000 lb. axle loading and a starting adhesion of 25 per cent each axle would exert 15,000 lb. tractive effort at start. This would require a 12 pole motor with a 12 in. commutator to bring the locomotive to 45 mi. per hr. with one motor per axle. Two motors per axle would give a maximum speed of 90 mi. per hr.

Assuming the maximum weight per axle held at 75,000 lb., then at 30 per cent adhesion, each axle could exert 22,500 lb. tractive effort at start. This would require 18 poles and 12 in. of commutator length to bring this locomotive to 45 mi. per hr. maximum speed and with a twin motor of the same dimensions the locomotive could be operated at 90 mi. per hr. maximum speed.

The design of the locomotive then becomes one of grouping the required number of axles under a cab to give the most economical operating unit. The grouping of axles under one cab depends on the required size of driver and this is where the dimensions of core and windings play an important part. At the present time twin motors can be built to go on 72 in. wheels and develop 25 per cent adhesion at start geared for 90 mi. per hr. maximum running speed. With the developments now under way, however, this wheel size may be brought down to 68 in. or the maximum speed on 72-in. wheels may be raised if desired, because the experience of the last few years indicates that considerable further improvements can be made to permit the application of smaller motors for the same tractive efforts or of the same size of motors for greater tractive efforts.

SUMMARY

1. The series single-phase commutator idea was conceived in 1884.

2. The developments on the high frequencies during this period diverted the efforts to the repulsion motor and the induction motor.

3. In 1902 B. G. Lamme gave the first real impetus to the application of the series single-phase motor to railroad application and recommended a low frequency.

4. In 1907 the New York, New Haven and Hartford Railroad electrification was the first outstanding application of the motor and these motors are operating successfully today on both alternating current and direct current.

5. Contemporary development in Europe led to standard system of alternating current only and brought out the shunted interpole motor.

6. In 1908 the electrical limitations were established of 2 bars per brush and 7 volts across the brush at start, also armature slots skewed to minimize telephone interference. The limitations hold today.

7. After the World War, a second big impetus was given to electrification by mechanical improvements.
   - a. Increased commutator peripheral speed.
   - b. Improved insulation.
   - c. Roller bearings.
   - d. More compact brush holders.

8. Further mechanical improvements followed in America.
   - a. Disk spring commutator.

b. More compact ventilation design.
c. Rolled steel and welded frames and housings.
d. Better punchings.

9. A united effort by all firms to produce a unit axle drive to simplify the design of locomotive.

10. Finally a return to the series single-phase commutator motor with shunted interpole.

In conclusion, it should be noted that our new design of series commutator motor and control equipment, for 25-cycle railway electrification, has exceeded expectations as to horse power per axle. A 4-axle locomotive, with the new motor, has developed more service capacity than was expected with the 6-axle locomotive which we proposed four years ago and which was then considered to be a marked improvement over existing designs. Further, it should be noted that this new design, while representing an entirely new analysis and proportioning or arrangement of the various essential parts, to obtain better power factor, efficiency, commutation, and speed-torque characteristics, is nevertheless based on the sure foundation of nearly thirty years of constant practical experience in a-c. electrification, and over three years of intensive development work and testing of this new design.

Lightning Investigation at Alcoa, Tenn.

BY J. ELMER HOUSLEY[1]

Associate, A. I. E. E.

Synopsis.—The cooperative lightning laboratories near Alcoa, Tenn., have been in operation since July, 1928. This paper outlines the purpose of the installation and describes the transmission line on which the studies are being conducted. A background is provided for a more complete appreciation of the technical data which appear from time to time. Conclusions drawn from an operating viewpoint are presented.

* * * * *

EARLY in 1928 there was a crystallization of the ideas concerning the use of the cathode ray oscillograph for field studies of lightning. The immediate result of this was the desire to establish two lightning laboratories in the field.

The Aluminum Company of America, through its subsidiary the Knoxville Power Company, afforded a transmission line of high insulation value and recognizing the importance of lightning investigation, joined the Westinghouse Electric and Manufacturing Company in a cooperative field research endeavor.

At the inception of this work the determining factors governing the selection of East Tennessee were the great number of thunderstorms, and the existence there, of the most heavily insulated steel tower transmission line in operation in the southeast at the time.

THE LINE

The transmission line selected for the investigation consists of two circuits operated at 150,000 volts and extends from Alcoa, Tennessee to the Santeetlah power house, a distance of thirty miles.

The elevation of Alcoa is about 700 ft. and the line travels over a rolling country until Tower No. 72 is reached when the line suddenly climbs to an elevation of 2,600 ft. A rugged country is traversed with several long river crossings until the Cheoah power house, at tailrace elevation of 1,080 ft., is reached. A further mountainous section is traversed to Santeetlah power house at elevation 1,270 ft. Data covering the first circuit of this line have been given in an Institute paper.[2]

The towers are double circuit to tower No. 60 and single circuit with horizontal configuration of conductors to tower No. 125 where double-circuit construction is resumed to the terminus at tower No. 152 at Santeetlah power house. See Fig. 1.

The configuration of the cables is vertical on the double-circuit towers with the middle wire offset 4 ft. 6 in. toward the tower, and the vertical separation is 11 ft. 9 in. at the top and 12 ft. 8 in. at the bottom. The single-circuit lines have a flat horizontal configuration with a spacing of 17 ft. 6 in. The conductor is 500,000 cir. mils A. C. S. R., 40 per cent steel by weight. The diameter is 0.904 in. The insulator strings are composed of ten disks in suspension and twelve in each of the triple strings used in a single dead-end assembly. Strap iron horn-gaps are used on the line and ground side and a horn is placed on each side of the insulator string over the axis of the cable in suspension units. The horns are arranged above the insulator for horizontal strings. The gap spacing is 3 ft. 9 3/16 in. The span between towers on the line varies from 650 ft. to 2,400 ft. The single ground wire of 1/2-in. high strength steel is common to both types of tower. This wire is located at the top and center of all towers. The single-circuit towers are provided with holes for the attachment of two additional ground wires, one between and above each outside cable and the center cable.

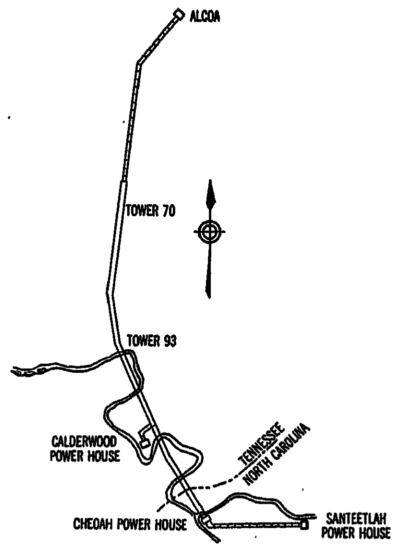


FIG. 1—DIAGRAM OF TRANSMISSION SYSTEM OF KNOXVILLE POWER COMPANY AND TALLASSEE POWER COMPANY

OPERATING EXPERIENCE

The lightning season extends from March 15th to October 1st. The insulator flash-overs occur mainly in the mountainous section of the line from tower No. 81 to tower No. 152. The original line, twenty-five miles long, has been in operation since April, 1919 and on this line the interruptions have averaged about ten per year. Lightning, with one exception, has been the sole cause of interruptions chargeable to the high-tension line.

1. Knoxville Power Company, Alcoa, Tennessee.

2. *The 150,000-Volt Transmission Line of the Knoxville Power Co.*, by Theodore Varney, A. I. E. E. JOURNAL, June, 1920, p. 563.

Presented at the Southern District Meeting No. 4, of the A. I. E. E., Louisville, Kentucky, November 19-22, 1930.

30-185

The exception concerns an obsolete type of strain insulator which failed several years ago on a special long span. No insulators have been found damaged by flashovers. The second circuit was added two years ago and five miles of double-circuit line was added making the total length of the line thirty miles. The second circuit and the added length of line has not increased the number of interruptions in the past two years.

Selection of Sites

After deciding upon two stations for the field investigations the location of the stations was selected after a study of the usual path of the thunderstorms. Previous observation had indicated that many storms traveled along the ridge of the Chilhowee Mountain which extended east and west and the line crossed the ridge at right angle. Along the south base of the mountain flowed the Little Tennessee river for a short distance until it reached a water gap and turned north. Many storms traveled up the short valley from west to east, probably due to the prevailing winds which are southwest.

It seemed appropriate to locate one station at the base of the mountain at the north near tower No. 70 and the other at tower No. 93, along the river near the base of the mountain on the south. See Fig. 2. The locations were near roads which would permit the transportation of building material and the apparatus required.

Satisfactory results were obtained from the station at

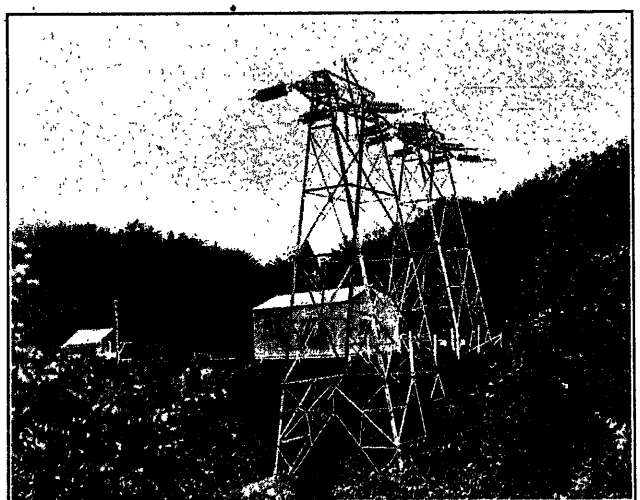


Fig. 2—Lightning Laboratory at Tower No. 93

tower No. 93, but the location at tower No. 70 was too remote from the storms on the ridge of the mountain and this station will be discontinued.

Klydonograph Equipment

Three klydonograph installations were established in conjunction with each station. All klydonograph potentiometers were of the three-phase type, one was located adjacent to each station and one on either side of the stations one mile distant. This is illustrated in Fig. 3. The klydonographs are equipped with eight-day clocks and the film records are removed weekly. A klydonograph was placed in a parallel circuit between the top of the tower and the ground at tower No. 93,

Fig. 3—Three-Phase Potentiometer and Klydonograph Installation

to study the potential gradient existing on the tower during a storm.

Description of Station

The station building at tower No. 70 is a frame building and at tower No. 93 is a sectional steel building. A partition provides a dark room and a kitchen, while a tent with a wood floor, provides the living quarters. An electric refrigerator furnishes storage for food supplies and a supply of cold water for the development of films.

A shallow well equipped with an electric pump supplies water to the station at tower No. 93. The other station pumps water from a mountain stream.

The frame building is lined with a heavy wire screen, well grounded, in the laboratory section and in the steel building it was only necessary to ground the structure at several points.

Equipment

The equipment in each station was identical. A gasoline-driven 15-kv-a.,110-volt, three-phase, 60-cycle, a-c. generator supplied power for station use. The direct-connected 1-kw. exciter furnished 125-volt direct current for use in the concentration coils on the oscillograph.

The Norinder oscillograph with its auxiliary equipment, consisting of vacuum pump, switchboard, linear timing device, oscillator, and high-voltage rectifier has been used throughout the tests and many improvements have been made in the apparatus and increased reliability has been obtained.[3] See Fig. 4.

An osiso was used for recording the output of a

3. *A Cathode Ray Oscillograph with Norinder Relay,* by O. Ackerman, A. I. E. E. Journal, April, 1930, p. 285.

microphone located some distance from the station to detect the location of the stroke by recording sound from the thunder, but the induction picked up on the long leads during the storms interfered, so that good results were not obtained. A potentiometer connected to an antenna was used to study air gradient potentials existing in the river valley and on the top of the ridge of Chilhowee Mountain.

Staff

Each lightning laboratory was continuously attended during the lightning season by two engineers from the Westinghouse Company, who made their residence at the station. During the winter various parts of the equipment were returned to the factory for alterations suggested by the preceding season's work.

The oscillogram No. C-3095-B, Fig. 5, was made during a storm July 10, 1930. These data have not yet been analyzed. The storms during the 1930 period, up to August 1, 1930, have been local thunderstorms and have covered only a very small area, and a small number of surges has been recorded at tower No. 93 and one at tower No. 70. Fig. 6 oscillogram shows a typical switching surge.

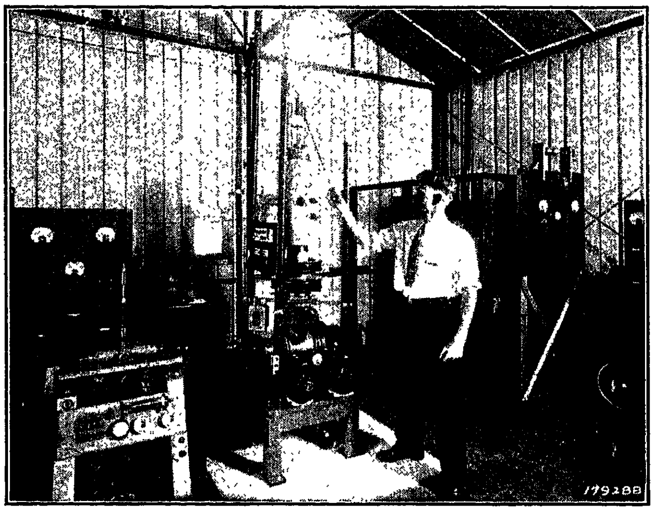


Fig. 4—Cathode Ray Oscillograph and Auxiliary Equipment in Laboratory at Tower No. 93

The small number of oscillograms obtained since the stations went into operation does not give a complete picture which would enable an analysis to be made of the waves appearing on the line with their exact point of origin and probable voltages which existed there. The data obtained and observations made during the past three years have been valuable in relation to the development of the cathode ray oscillograph and demonstrated the importance of this device in the field.

Conclusions

Since the location of storms must be very close to the station, chance plays a large part in the volume of data obtained. Accordingly it is hoped that by continuing the investigation over a period of time that a sufficient number of surges will be recorded so that a complete analysis may be made of the various types and determine the efforts of the natural strokes.

One of the first observations made indicated that the line trip-outs were caused by direct strokes and not by induced charges. Many strokes come very close to the line and near the oscillograph with no record obtained although a surge of two times normal would be quite legible.

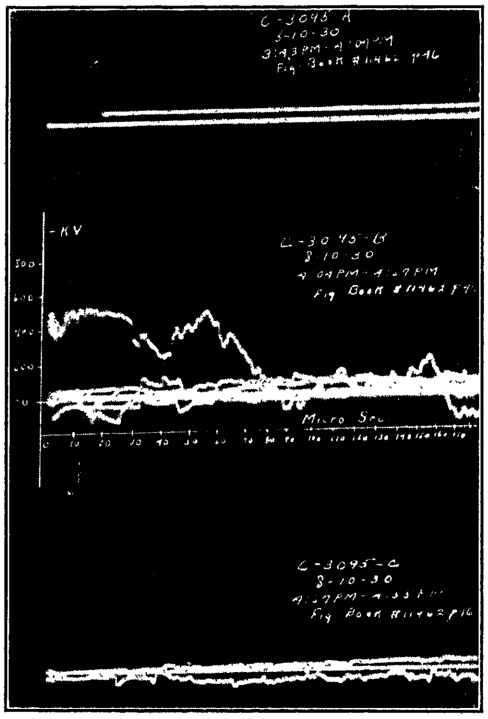


Fig. 5—Oscillogram of One Large Lightning Surge and Several Minor Surges

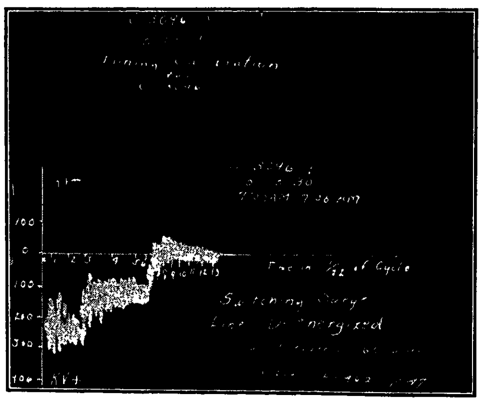


Fig. 6—Switching Surge when Deenergizing Line

One conductor alone is involved during a stroke on the line and often it is the first wire adjacent to the approaching storm. The oscillograph is attached to only one conductor and a line tripout has resulted from

a stroke near the station but with a very small surge recorded on the oscillograph. A heavy surge would be recorded by the klydonograph on some other conductor. Conversely a heavy surge may be recorded on the oscillograph and the klydonograph on the same conductor while the other two conductors will have very light surges shown.

The klydonographs located one mile from the station have shown surges beyond the calibration range and the oscillograph would show a light surge indicating the attenuation which occurs.

Low resistance tower footings and a low resistance ground wire were indicated as desirable for decreasing flashovers. Due to the line being built over an almost solid rock country with a light covering of weathered rock, some artificial means of lowering tower footing resistance was indicated.

No damage to insulators from flashovers has been experienced in ten years operation and no burns on the cable were found during the last inspection made two years ago when each tower was climbed. Ground current relays have not been used but will be installed in the future. The generating capacity on the line varies from 130,000 to 150,000 kv-a., and at times the system operates in parallel with another large system through a 25,000-kv-a. auto-transformer bank.

Discussion

J. J. Torok: The investigation work carried on in Tennessee has been exceedingly fruitful. The number of records obtained has not been astonishingly large but the nature of those which were obtained is such that it exposed serious discrepancies in the early theories and aided considerably in establishing a more consistent concept of the origin and manner in which surges appear on the line and their nature.

The early concepts of the formation of surges on lines were predicted on the inductive theory, that is that the bound charge on the transmission line was released suddenly when the cloud discharged. Accordingly, all the transmission line designs were based purely on this theory. The value of ground wires was intimated on their protective ratio. The insulation on the lines was determined by height and ground wire location and many other minor details were governed purely on this basis, yet these lines do not show a very marked improvement over those which had been built according to the dictates of construction economics only.

The first season's operating experience bore strong evidence against the induced voltage theory. Many storms raged about the station and over the line yet only one record was obtained in which the voltage rose above three times the operating value. The records of the operators showed clearly that of the hundreds of strokes appearing over or near the line only one or two resulted in a surge on the line which might be harmful in its character. The oscillograms of these surges showed that they were of long duration ranging from 30 to several hundred microseconds which again was contrary to the earlier concepts which dictated waves of short duration ranging from perhaps one or two microseconds to 15 or 20. Using these records as a basis and also those which were obtained later on oscillograph stations located in Chicago, New Jersey, and Arkansas, a series of calculations was made to determine the probable magnitude of induced surges. These calculations showed that if the clouds discharged in a period of time indicated by the oscillograms that the induced voltages would hardly exceed one or two hundred thousand volts which is a value quite harmless to high-voltage transmission lines. Then the direct stroke theory was ushered into prominence. In the past direct strokes were always considered as an irresistible force which man could not yet cope with. However, this realization, that the surges which we have been protecting against in the past were the results of lightning volts coming directly in contact with the line instead of originating by induction, gave the engineers renewed hope in their strive for the ideal—the lightning-proof line.

The direct stroke theory dictates that if the line is to be made immune from lightning it must have some protection against these direct strokes. The ground wires which have been used in the past still seem to be a good solution for the lightning problem, however, modifications must be made so that the new concepts can be satisfied, namely, that these ground wires should be so placed that the stroke itself must terminate on the ground wire rather than on the conductors. This meant that the ground wires must be placed well above the conductor and also in such a position that the ground wires protect not only one but all three conductors. Furthermore, the estimates and measurements of the currents in the lightning bolt dictated that the tower and footing impedances should be very low so that the tower itself will, when carrying these heavy currents, not rise up to a high potential above earth and thus cause flashover from the tower to the conductor. Analysis of a number of transmission lines indicated very strongly that this direct stroke theory will be much more useful than its predecessor. Lines which either by chance or design were located in a terrain where low tower footing resistance could readily be obtained had exceedingly good operating records, one especially which had an average tower footing resistance around two or three ohms has only had one outage in five years, whereas a line of similar design but going over mountainous country where the tower footing resistance ranged from a few ohms to several hundred has an average of five or six outages per year. Further analysis on the position of the ground wires also shows that where only one ground wire is situated in the middle and close to the conductor the performance is very poor. An exceedingly marked improvement is obtained in installations where two ground wires are so situated with respect to the conductors that they shield them physically.

Another question which has been less pressing in the engineers' mind is that of switching surges. Here again the experimental stations in Tennessee have been of considerable importance. They have made records of switching surges that occurred during the normal operation of the line. These records indicated that a normal switching surge will seldom exceed three times normal and only rarely rise to four times normal. Such switching surges are of great value in that they will indicate the minimum insulation a transmission line can have and still give good operating records. All these data and much more can be attributed directly or indirectly to the Tennessee investigation.

Operating Experience With Reactance Type Distance Relays

BY E. E. GEORGE[1]

Member, A. I. E. E.

Synopsis.—*In view of the fact that reactance type distance relays have been in service in this country less than a year, operating experience should be of general interest to the industry at this time. This paper presents the performance record during the 1930 lightning season of two new types of reactance relays. One of these types is a high-speed American built relay, using a stepped time-distance characteristic. The other relay, using a sloped time-distance characteristic is European built, but designed for a more conventional speed of operation.*

These relays have performed satisfactorily on long transmission lines with wide variation in short-circuit conditions. The correctness of the reactance principle has been demonstrated. Certain difficulties with these relays have arisen on interconnections operating near the stability limit. Both definite and tentative conclusions from this year's operating experience are included in the paper.

* * * * *

Dates of Installation

On February 9, 1930, the Tennessee Electric Power Company installed three reactance relays at their Great Falls Hydro Plant. These relays were of the normal speed distance type (LB-1) and were furnished by the American Brown Boveri Company, but were built in Baden, Switzerland, by Brown Boveri, Limited. This is believed to be the first installation of reactance relays in this country.

On February 19, 1930, the Tennessee Electric Power Company set up a temporary test installation of three General Electric high-speed reactance type (GAX) distance relays at their Ocoee No. 1 Hydro Plant. These same relays were permanently installed at West Nashville Substation on February 23, 1930. The Ocoee installation was the first in this country of American built reactance type distance relays.

Another installation of Brown Boveri type LB-2 relays was made at Ocoee No. 1 on February 25, 1930, and another installation of GAX distance relays was made at Centerville Substation on March 30, 1930.

Since the above time 21 more Brown Boveri type LB-1 relays and 21 more General Electric type GAX relays have been installed, making a total of 54 distance relays of the reactance type on this system. In addition to the above, six high-speed distance relays of the Westinghouse impedance type (HZ) are now being installed.

Figs. 1 and 2 are typical wiring diagrams for the two types of reactance relays and show how the test facilities preferred by this company have been applied. If it is desired to use the auxiliary equipment offered by one manufacturer for securing ground protection as well as phase protection, the test scheme becomes more complicated.

Reasons for Installation

The reasons for the rapid installation of these new types of relays may be of general interest. Herewith is given a tabulation of the variation in short-circuit kv-a. on the various high-tension buses of this system. This variation is due chiefly to changes in operating

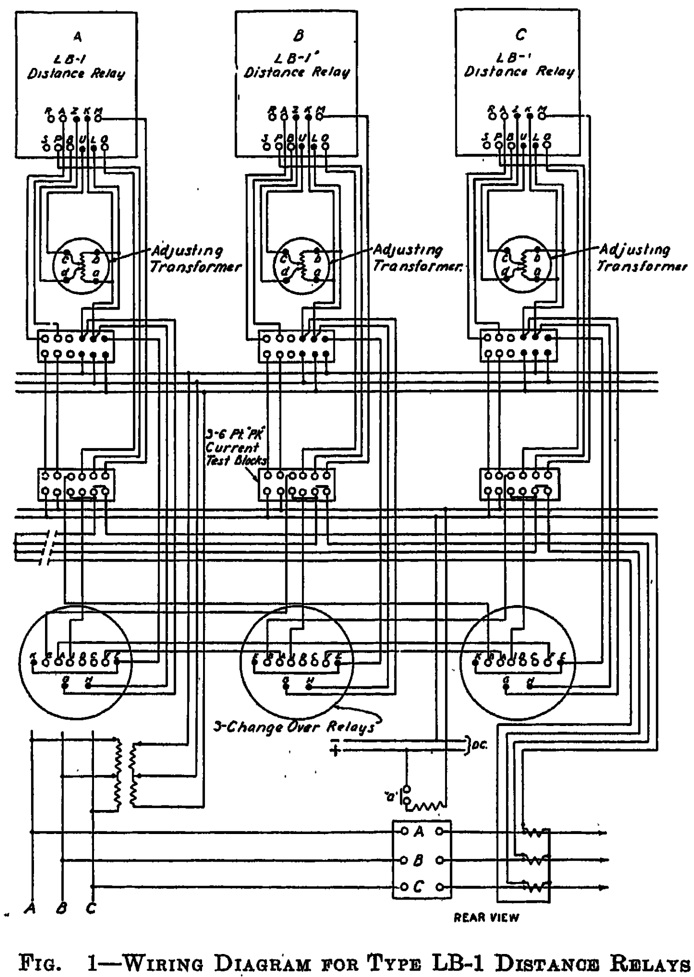


Fig. 1—Wiring Diagram for Type LB-1 Distance Relays

conditions with steam and hydro generation at widely different locations. The tabulation covers the total short-circuit kv-a. on the bus, and any one outgoing line has substantially less current.

1. Supt. of Electrical Operation, Tennessee Electric Power Company, Chattanooga, Tennessee.

Presented at the Southern District Meeting No. 4, of the A. I. E. E., Louisville, Kentucky, November 19-22, 1930.

Fig. 3 shows the location of circuit breakers on the 154-kv. and 110-kv. systems together with the type of phase protection now in service at each. Many of the line sections are of No. 2/0 copper or equivalent. This map together with the table of short-circuit kv-a. shows why the short circuit at the end of a long section may be even lower than the normal load of the line. Furthermore the opening of a section under fault frequently requires the adjacent sections to carry as much as twice normal load for a minute or more. Over-current relays (and relays having over-current pick-up) have proved inadequate and almost useless under these conditions.

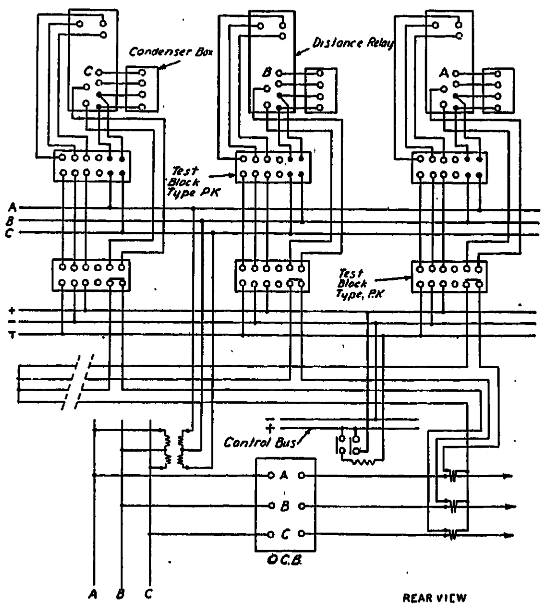


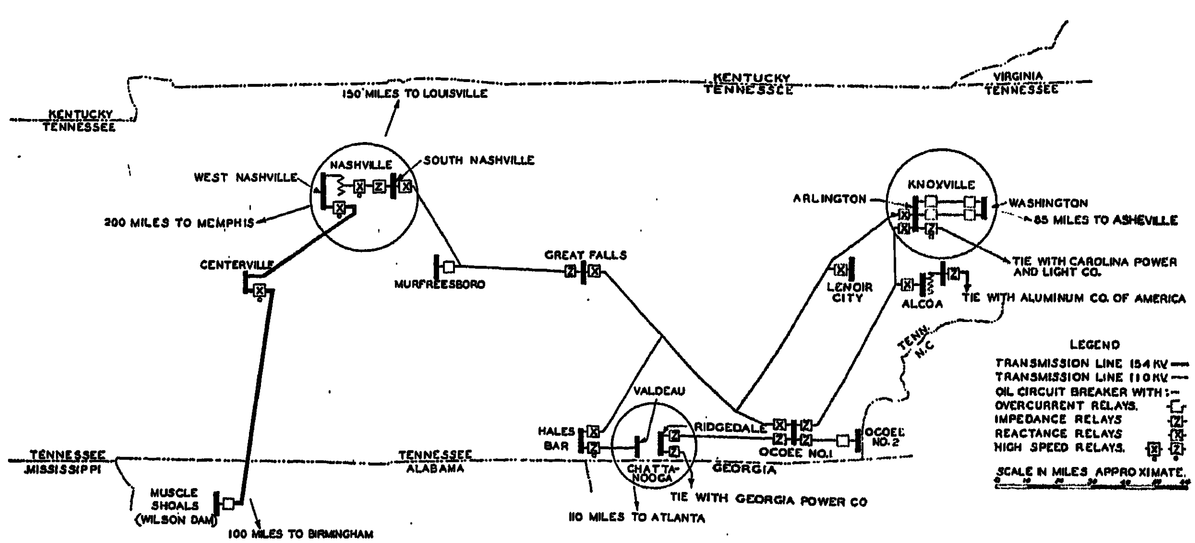
Fig. 2—Wiring Diagram for Type GAX Distance Relays

TABLE I
VARIATION IN SHORT-CIRCUIT KV-A. ON TENNESSEE ELECTRIC POWER SYSTEM

	Maximum	Minimum
Arlington	680,000	160,000
Centerville	360,000	170,000
Great Falls	480,000	210,000
Hales Bar	600,000	250,000
Ocoee No. 1	780,000	250,000
Ridgedale	560,000	220,000
West Nashville	390,000	180,000
Wilson Dam	800,000	150,000

The principle of the distance relay finds a ready application in handling this situation. Reactance type relays were preferred over the impedance type since it is thought that the former give a more accurate measurement of the distance to the fault by being independent of arc resistance. This was given considerable weight on account of the fact that the resistance of many lines on this system constitutes an appreciable proportion of their impedance. Reactance type relays have another advantage over impedance relays as now built when applied to lines having low minimum short circuit compared to maximum load. Since distance measurement is taken care of by the reactance meter, the impedance release or starting unit may be designed to have its release characteristic vary with the voltage. At 20 per cent of normal voltage, both types of reactance relays considered will release with current below 10 per cent of that required to release them at normal voltage.

All future installations on the 154-kv. and 110-kv. systems will probably be reactance type distance relays, although one short line will soon be equipped at both ends with an experimental installation of high-speed impedance type (HZ) distance relays. In selecting distance relays to date more attention has been paid to getting low pick-up under minimum generating conditions for long lines, than in securing high speed, although high speed will be more of a factor as high-speed breakers are installed generally over the system.



PHASE PROTECTION OF 154 AND 110 KV. SYSTEMS

Fig. 3—Location of Distance Relays on Tennessee Electric Power System

Operating Experience

Both types of reactance relays have, in the opinion of the writer, demonstrated the following conclusions beyond question:

1. Reactance relays will protect each section of line selectively without cascading settings. Each section of line is thus protected independently of other sections.

2. The amount and location of generation has no appreciable effect on the time of clearing faults. Any secondary current of about 2 amperes or over will operate the relay in a predetermined time if the voltage is low enough to indicate a fault in the protected zone.

3. Loads much beyond the sustained thermal capacity of a transmission line can be carried without danger of tripping. With normal bushing current transformer ratios, the relays will carry from 500 to 1,000 amperes primary current, whereas the normal rating of the average high-tension transmission line is probably 250 to 350 amperes. Sustained currents of about ten times normal rating will fuse the average line. Sustained currents of possibly five times normal rating will cause failure of a line under normal tension. Frequently it is desired to carry twice normal load on a transmission line for a few seconds and there is no thermal limitation to doing this, but it is usually impossible with the ordinary overload relay. In case of a non-attended station, it may be necessary to back up the distance relays with some other type of relay following more closely the thermal characteristic of the transmission line. Ordinarily the operator or load dispatcher will notice promptly any unusual diversion of power and take steps to reduce the load.

4. Impedance releases or starting units on reactance relays should be set rather high—ten amperes or more, at normal voltage.

5. High-tension potential supply is necessary in practically all cases. If this is not provided there will be a certain percentage of incorrect operation due to trouble on the lower voltage system. Selectivity will suffer with the use of low-tension potential supply, not only on account of the impedance of the power transformers but also because of the voltage balancing action of certain power transformers during single-phase faults. In addition to the above difficulties potential supply from the delta winding of a grounding transformer will tend to cause incorrect phase relay operation on ground faults.

6. Potential transformers are the best and most economical form of potential supply, in the long run. This statement is made advisedly after trying various substitutes. The lower first cost of capacitance coupling devices may be more than offset by the additional cost of adjustment and test. A change in secondary loading at any time requires almost as much work as the initial adjustment and test. The volt-ampere output is limited, and is inadequate for some types of relays. The phase angle error of capacitance devices is considerable at very low voltage, where accuracy is most essential for reactance relay potential supply. Furthermore, when high-tension potential supply is installed for relays, there is a tendency to use it for synchronizing, voltage indication, frequency indication, indicating meters, watthour meters, etc. It is clearly impossible for capacitance devices to handle such burdens, whereas 500-volt ampere potential transformers will safely handle all the potential burdens in the station.

7. Pilot indication on potential supply is desirable. Neon lamps serve this purpose admirably.

8. If it is desired to take advantage of the special characteristics of distance relays for fast bus protection, it is not possible to get correct directional action in all cases for heavy faults close to the station.

9. The cost and importance of distance relay installations justify complete and accurate operating records, and a careful study of these records after they are obtained. The average substation operator will not, unless especially instructed, report with sufficient care and thoroughness on the performance of such relays. Even if the operator normally has plenty of time to make the proper records, knows the names and functions of the major parts of the relay and has facilities for promptly reporting to the dispatcher, there will frequently be times when so many things happen at once that he is unable to tell just what occurred. If he attempts to guess at what happened, such misinformation is much worse than no information at all. In spite of such handicaps there will be occasions when a good operator, well trained, can give very valuable information on relay operation.

10. Automatic oscillograph installations should be very valuable in analyzing distance relay operation, especially on occasions when the station operator's time is limited.

11. Quick trip ammeter installations as used to record neutral ground current, have been very helpful. The absence of a ground current record indicates a phase-to-phase short circuit which should operate the distance relays. These graphic ammeters frequently show ground current at the same time the distance relays operated, indicating a two-phase-to-ground short circuit, or a phase relay operation on a single-phase-to ground fault.

12. In this territory most of the high-tension phase relay operations occur during the height of the lightning season in June, July, and August, thus giving a rather limited time in which to make and note the effect of any changes in relay installations. This means that questionable or incorrect operations must be followed up very promptly in order to note the effect of any improvement or revision before the lightning season ends. The lightning storms are not only concentrated during the summer months, with a peak in July, but these storms also occur most frequently in the afternoon. Figs. 4, 5, and 6 show clearly that the major portion of each year's lightning occurs between the hours of 1:00 p. m. and 5:00 p. m. in June, July, and August. This extreme concentration of trouble greatly complicates relaying and dispatching problems due to independent troubles occurring close together, or even

simultaneously. A second line may relay out before the first line can be closed back in, thus leading to confusion in the operating records as well as to interruptions to customers provided with two or more sources of supply, even though none of the circuits go in trouble permanently.

13. One type of reactance relay is equipped with a distance indicator which has been very helpful in studying the conditions under which the impedance release operated. It would also be desirable to have more than one target on the step-by-step distance relays so that there would be a record of whether the relay tripped on instantaneous, intermediate or back-up time. It has been found impracticable to determine this by watching the relay, even on staged tests.

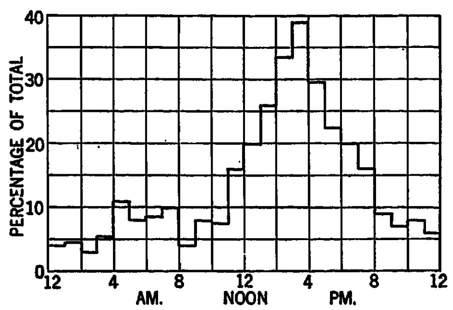


FIG. 4—HOURLY DISTRIBUTION OF INTERRUPTIONS DUE TO LIGHTNING

14. No entirely satisfactory method of low-voltage routine tests has been devised for distance relays. They have been checked by staged tests during installation, and occasionally thereafter in case of questionable operation.

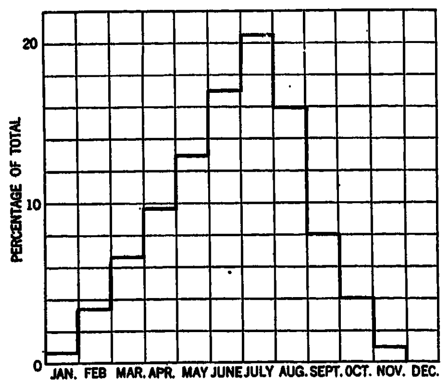


FIG. 5—MONTHLY DISTRIBUTION OF LIGHTNING STORM DAYS

15. Both types of reactance relays have been found to operate on arc faults in the same time as on solid short circuits, even up to the longest arcs that could be maintained on the system.

OPERATING PROBLEMS

In addition to the foregoing conclusions regarding distance relay performance, there are certain questions which, in the opinion of the writer, have not been definitely answered as yet. These are outlined below, together with some of the evidence that may be helpful in reaching conclusions, especially when and if corroborated by further experience.

Tables II, III, and IV cover the operation of distance relays on this system from the dates of their installation up until the present time. From these detailed records the reader may analyze the available evidence in brief and form his own conclusions in the light of his own experience and his own particular operating conditions.

1. Apparently the operation of all types of distance relays is highly satisfactory on radial feeders. The only difficulties arise on trunk lines and on interconnections.

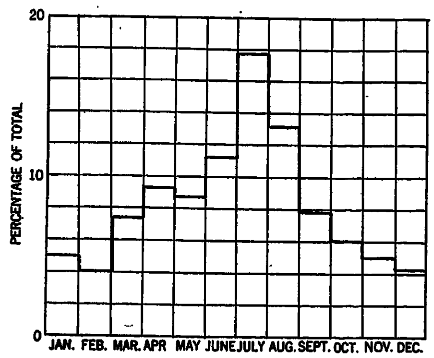


FIG. 6—MONTHLY DISTRIBUTION OF RELAY OPERATIONS

2. The performance of distance relays under out-of-step conditions is still uncertain. This liability is not confined to these relays, as it is definitely known that the old impedance relay will operate quickly on any out-of-step condition if the current peaks exceed the pick-up value for a short time. Both laboratory and field tests show that one type of reactance relay will operate on out-of-step conditions if the frequency of surging is very low or very high. Another type seems

TABLE II

SUMMARY OF REACTANCE RELAY OPERATIONS

Through September 30, 1930

Correct operations	47
Questionable operations	7
Wrong operations	0
Inadequate potential supply	18
Total	72
Analysis:	
Correct operations	
Line relayed at one end only	3
Same line relayed simultaneously at other points	28
Line relayed while being supplied from one end only	5
Back-up protection	3
Low-tension bus failure	1
Bad synchronizing	5
Bus protection	2
Total	47
Questionable operations	
Out-of-step conditions	7
Total	7
Inadequate potential supply	
Cross phased	3
44-kv. trouble	5
Bushing potential devices	5
110-volt secondary trouble	5
Total	18

3. Even if out-of-step conditions should cause relay operation, many interconnections are subject to more or less prolonged surging somewhat below the stability to be reasonably immune to ordinary out-of-step conditions but severe surges may cause incorrect operation. The recently completed tie in East Tennessee interconnecting about 5,000,000 kw. in the north and 1,000,000 kw. in the south is particularly subject to bad surges. This problem is being actively studied at the present time. Unfortunately there is no precedent for saying that a line should or should not relay on out-of-step conditions. The Relay Subcommittee of the Southeastern interconnection has tentatively suggested that severe out-of-step conditions should cause relay operation, but only at one location, which should be at the point of maximum voltage variation.

TABLE III

DETAILS OF LB RELAY OPERATIONS

6 Installed in February 1930
3 Installed in May 1930
3 Installed in June 1930
6 Installed in July 1930

Station	Line	Date	Time	Cause
Ocoee No. 1	Nashville	3-20-30	11:20 a. m.	Open potential circuit
Great Falls	Cleveland	3-23-30	10:27 a. m.	Potential network
Great Falls	Cleveland	3-23-30	1:18 p. m.	Potential network
Great Falls	Cleveland	3-23-30	1:41 p. m.	Potential network
Great Falls	Cleveland	3-26-30	11:58 a. m.	Potential network
Ocoee No. 1	Nashville	6-21-30	3:07 p. m.	Lightning
Great Falls	Cleveland	7- 2-30	11:21 p. m.	Wilson Dam out of step
Great Falls	Cleveland	7-10-30	2:11 p. m.	Nashville out of step
Great Falls	Cleveland	7-10-30	2:12 p. m	Bad synchronizing
South Nashville	Great Falls	7-13-30	2:31 a. m.	Bus failure
Arlington	Maryville	7-13-30	6:35 a. m.	Lightning
Arlington	Cleveland	7-13-30	5:49 p. m.	Lightning
Arlington	Maryville	7-16-30	7:43 p. m.	Lightning in Georgia
Arlington	Cleveland	7-23-30	12:08 p. m.	Lightning
Arlington	Cleveland	7-23-30	1:04 p. m.	Lightning on double-circuit line
Arlington	Maryville	7-23-30	1:04 p. m.	Lightning on double-circuit line
Arlington	Maryville	7-23-30	1:14 p. m.	Lightning
South Nashville	Great Falls	7-23-30	5:08 p. m.	Lightning near Centerville
Great Falls	Cleveland	8- 9-30	2:04 p. m.	Lightning
Ocoee No. 1	Nashville	8- 9-30	2:04 p. m.	Lightning
Arlington	Maryville	8-10-30	3:20 p. m.	Bus protection
Arlington	Cleveland	8-10-30	3:20 p. m.	Bus protection
Arlington	Cleveland	8-14-30	7:26 a. m.	Lightning
South Nashville	Great Falls	8-14-30	7:57 a. m.	Lightning near Wilson Dam
South Nashville	Great Falls	8-14-30	6:32 p. m.	Lightning on W. Nash. line near S. Nash
Arlington	Cleveland	8-21-30	3:40 p. m.	Lightning
South Nashville	Great Falls	9- 8-30	8:38 a. m.	Lightning
Arlington	Cleveland	9- 8-30	10:44 a. m.	Lightning

limit and relays should hold in all such surges. This is one of the problems on the East Tennessee interconnection.

4. Wide variations in power factor during load swings seems to be one of the chief difficulties in applying reactance type relays to trunk lines and interconnections.

5. Impedance releases or starting units should have reset values fairly close to the release values, particularly if the starting unit is non-directional. Otherwise a fault may be cleared promptly at some other location, but the resulting surging or readjustment of power flow may be sufficient to hold the relay released and cause incorrect operation.

6. It would be advantageous for the starting units to be made more readily adjustable. At present they are designed and factory adjusted so as to give back-up protection to two or three average sections of line, while the distance measuring element is very flexible and can be adjusted for most any combination of sections. This arrangement is quite satisfactory as far as actual short circuits are concerned, but does not take care of the difficulties of load and power factor swings encountered on interconnections. Obviously a reactance meter, if allowed to operate under these conditions, will perform somewhat erratically. The logical remedy seems to be to adjust the release unit to operate on faults just a little beyond the nearest breaker, and use some separate form of back-up protection if desired.

7. The time setting on intermediate and back-up operation of step-by-step distance relays should be rather long—probably 60 cycles or more for the intermediate time—if used on heavy interconnections. This is a tentative conclusion from operating experience on the East Tennessee interconnection.

8. It may be possible to have the instantaneous element on a distance relay operate too quickly. Incorrect operation may occur due to breaker adjustment if the relay trips under two or three cycles.

9. There seem to be certain complications in using the bus protection feature of distance relays, and it is recommended that important stations be protected by some independent form of bus protection so that distance relays can be used for outgoing protection only.

10. It does not seem to be wise to try to speed up the initial time too much on certain types of relays. A certain definite time is required for proper directional discrimination.

TABLE IV
DETAILS OF G A X RELAY OPERATIONS
3 Relays installed in February 1930
3 Relays installed in March 1930
6 Relays installed in September 1930

Station	Line	Date	Time	Cause
West Nashville	Centerville	3–29–30	12:01 p. m.	Air break switch arced between phases
Centerville	West Nashville	4– 6–30	4:17 p. m	44 kv. bus switch opened by mistake
Centerville	West Nashville	6– 7–30	4:14 p. m.	Potential circuit opened by mistake
West Nashville	Centerville	6–19–30	10:02 a. m.	Insulator failure
Centerville	West Nashville	6–30–30	3:15 p. m.	Lightning near Great Falls
Centerville	West Nashville	6–30–30	3:17 p. m.	Bad synchronizing
Centerville	West Nashville	7– 7–30	6:45 p. m.	Lightning
West Nashville	Centerville	7– 7–30	6:45 p. m.	Lightning
Centerville	West Nashville	7–10–30	2:11 p. m.	Lightning near Great Falls
West Nashville	Centerville	7–10–30	2:22 p. m.	Lightning
Centerville	West Nashville	7–10–30	2:53 p. m.	Lightning on 44 kv.
West Nashville	Centerville	7–10–30	3:10 p. m.	Lightning
West Nashville	Centerville	7–10–30	4:10 p. m.	Lightning
Centerville	West Nashville	7–10–30	4:10 p. m.	Lightning
Centerville	West Nashville	7–11–30	12:12 p. m.	Lightning near Great Falls
Centerville	West Nashville	7–11–30	3:09 p. m.	Centerville transformer failed
Centerville	West Nashville	7–17–30	5:58 a. m.	Bad synchronizing
West Nashville	Centerville	7–18–30	1:34 p. m.	Bad synchronizing
West Nashville	Centerville	7–23–30	5:08 p. m.	Lightning
Centerville	West Nashville	7–23–30	5:08 p. m.	Lightning
West Nashville	Centerville	7–23–30	5:23 p. m.	Centerville by-passed
Centerville	West Nashville	7-24–30	1:22 p. m.	Lightning
West Nashville	Centerville	7–24–30	1:22 p. m.	Lightning
West Nashville	Centerville	7–24–30	1:26 p. m.	Bad synchronizing
Centerville	West Nashville	7–24–30	1:57 p. m.	Wilson Dam out of step
Centerville	West Nashville	7–25–30	3:24 p. m.	Lightning
West Nashville	Centerville	7–25–30	3:24 p. m.	Lightning
West Nashville	Centerville	7–25–30	3:48 p. m.	Lightning
Centerville	West Nashville	7–29–30	2:31 p. m.	Lightning on 44 kv.
West Nashville	Centerville	8– 9–30	2:04 p. m.	Lightning south of Centerville
Centerville	West Nashville	8–14–30	7:25 a. m.	Lightning on 44 kv.
West Nashville	Centerville	8–14–30	11:06 a. m.	Lightning south of Centerville
Centerville	West Nashville	8–14–30	2:29 p. m.	Loose connection
Centerville	West Nashville	8–14–30	6:32 p. m.	Loose connection
Centerville	West Nashville	8–14–30	8:32 p. m.	Loose connection
Centerville	West Nashville	8–14–30	9:17 p. m.	Lightning
West Nashville	Centerville	8–14–30	9:17 p. m.	Lightning
West Nashville	Centerville	8–17–30	3:12 p. m.	Lightning
Centerville	West Nashville	8–17–30	3:12 p. m.	Lightning
West Nashville	Centerville	9– 8–30	6:11 a. m.	Lightning
West Nashville	Centerville	9– 8–30	8:38 a. m.	Lightning
West Nashville	S. Nashville	9– 8–30	8:38 a. m.	Lightning
Centerville	Wilson Dam	9–13–30	12:27 p. m.	Lightning
Centerville	Wilson Dam	9–24–30	6:19 a. m.	Insulator failure

11. Relay settings or schemes should not be modified on account of one report of incorrect operation. It is too difficult for the average operator to determine exactly what happened, and except in case of careful observation on staged test, too much weight should not be given any one reported erratic performance.

12. It is entirely feasible to use separate and independent ground protection with distance relays. It has always been the practise of this company to use current directional ground relays for ground protection, and no change was made in this practise when distance relays were installed for phase protection. However, both manufacturers have developed schemes of ground protection using distance relays and star potential supply.

13. Distance relays can be used successfully on the same system with other types of relays. However, if the ordinary types of relays operate slowly under minimum generating conditions the distance relays will frequently operate ahead of them.

Summary

Operating experience has shown the correctness of the major principles of design and application of reactance type distance relays on this system. Several difficulties have been encountered but these have been given less weight than the prime considerations of carrying high load safely during emergency and of clearing the majority of faults selectively during all operating conditions.

Discussion

J. B. MacNeill: Mr. George states:

"Potential transformers are the best and most economical form of potential supply in the long run."

This is admittedly so where very large secondary burdens are to be handled, or where extreme accuracy of phase angle is required. However, the fact remains that successful operation on many large systems, including relaying, indicates definitely the worth of bushing potential devices when used within their ratings. The low cost of these devices and the elimination of high-voltage potential transformers justify the bushing potential device where usable.

Looking to the future, it is reasonable to expect that auxiliary devices, such as relays, volt meters, synchronoscopes, etc., will all have reduced burden, thus broadening the application of low output sources of potential. Recent improvements in bushing potential devices have reduced phase-angle error considerably over wide voltage range. The error now obtainable at 10 per cent of normal operating voltage is not greater than 20 per cent of previous value.

Lighting Airway Beacons
Direct From High-Voltage Transmission Lines

BY F. W. CARTLAND[1]
Associate, A. I. E. E.

Synopsis.—Airway beacons requiring from 1½ to 2½ kw., may be lighted direct from low-voltage distribution lines, gas engine-driven generators or from high-voltage transmission lines. The latter requires a high potential transformer of very small capacity, although most standard high potential transformers are made only in ratings of 15 to 100 kv-a.

The "capacitap" is a potentiometer device similar to that used with condenser bushing terminals, the capacities being composed of suspension type capacitor units. The capacitap will give satisfactory performance for certain types of loads. The device is very well adapted to the supply of power to airway beacons having nearly constant load and approximately 100 per cent power factor where not more than 3 kw. is required. The construction and performance are discussed in detail.

Introduction

The rapid progress of aviation during the last few years has emphasized the need of adequately lighted airways. The airports have been located near the cities where electric power for flood lights and searchlights was readily available. However, the supply of power to airway beacons in isolated places has been a more difficult problem. Beacons in such localities have been operated from low-voltage transmission lines or where these were not available, gas engine-driven generators have been used. The power required for such installations is approximately 2 kw., and low capacity transformers are available where the system voltage does not exceed 23,000 volts. When higher voltage lines are encountered the smallest standard transformers built vary from 15 to 100 kv-a., increasing with the system voltage. A 100-kv-a. transformer used to deliver but 2 kw. is not only expensive but also inefficient.

A paper presented by Messrs. Spracklen, Marshall, and Langguth at the Winter Convention in New York, February 13-17, 1928, described a potentiometer device for use with condenser type bushings, which supplied sufficient power for operating relays and synchronizing equipment. With the development of high-voltage outdoor capacitors of the suspension type, developed the possibility of adapting them to a potentiometer circuit which would supply greater amounts of power than could be obtained from a condenser bushing. While the capacitor could be thus used to supply very great quantities of low-voltage power, the capacitors as built at present are of such a size and construction that it is not considered desirable or economical to obtain more than 2 or 3 kw. from such a circuit.

Description of Capacitor Power Supply

The capacitor power supply or "capacitap," consists essentially of a number of suspension type capacitors connected in series with a portion paralleled by the load and a reactor in series as shown in Fig. 1. Since in most cases the load voltage is 110 volts, the use of a small transformer (11,000/110) as shown in Fig. 2 is more desirable considering the capacitor economy. Another modification of this circuit, as shown in Fig. 3, has an additional advantage in that the full load

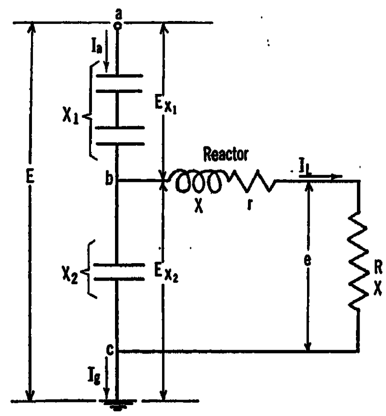


Fig. 1—Theoretical Circuit—Single Line to Ground

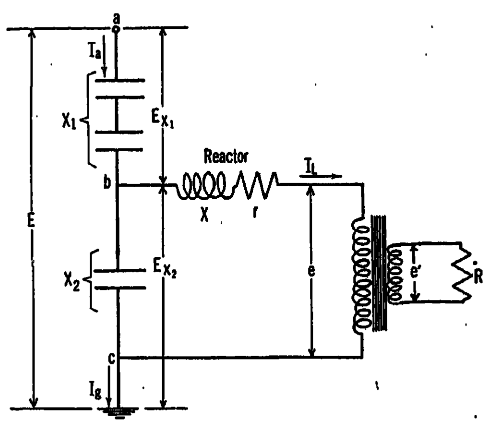


Fig. 2—Single Line to Ground Using Small Transformer

ground current is much less than that of the equipment shown in Fig. 2. (Considering circuits which produce the same voltage regulation.)

A capacitap as shown in Fig. 4 was built for studying the performance and practicability of this circuit. This equipment, built for supplying 2½-kw. unity

1. Capacitor Engineer, Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa.

Presented at the Southern District Meeting No. 4, of the A. I. E. E., Louisville, Kentucky, November 19-22, 1930.

30-179

power factor at 110 volts from a 66-kv. line had load voltage curves as shown in Fig. 5. The curve of Fig. 6 shows the result of varying the size of reactor. The complete circuit as shown in Fig. 7, consisted of eight low-voltage capacitors, sixteen high-voltage capacitors shown in Fig. 8, a standard transformer, a reactor and two enclosed spark gaps. Both transformer and reactor were tapped to give the desired adjustments. Each of the low-voltage capacitors was 0.020 μf., 10,000 volt and each of the high-voltage capacitors was

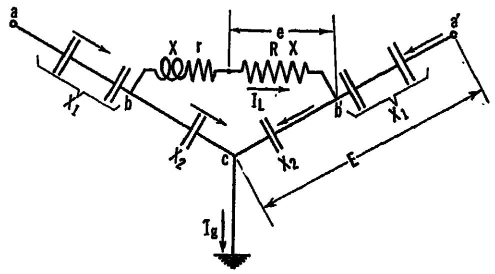


FIG. 3—THEORETICAL CIRCUIT—DOUBLE LINE TO GROUND

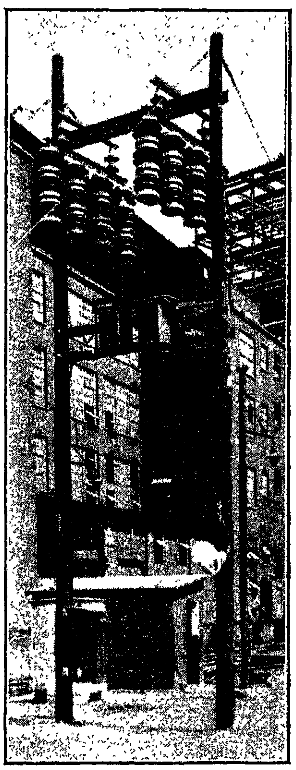


FIG. 4—EXPERIMENTAL INSTALLATION (2½ KW. FROM 66 KV.)

0.008 μf., 16,000 volt. The reactor was designed for 14,000 volts and had 176 henrys maximum inductance. The spark gaps were placed in parallel with capacitors $b\,c$ and $b'\,c$.

The individual capacitor unit is shown in Fig. 8. It is similar in design to those used for carrier current applications, but is a special rating. The construction is such that the capacitor will flash over the outside of the porcelain before it will flash through the inside. The characteristics are similar to those for line insulators. The wet flashover at 60 cycle is 70 kv. and the dry flashover is 116 kv. The weight of each capacitor is approximately 115 lb.

INSTALLATION

The capacitap may be installed in several ways such as suspending from an existing tower or from a tower or pole erected especially for carrying this load. The weight of the complete equipment shown in Fig. 4, is about 3,000 lb. The equipment may be connected

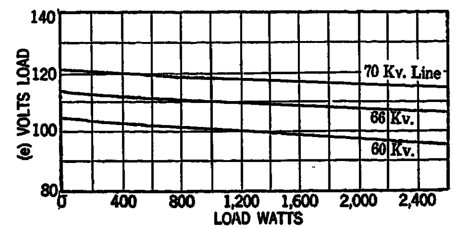


FIG. 5—LOAD VOLTAGE CURVES. (EXPERIMENTAL INSTALLATION)

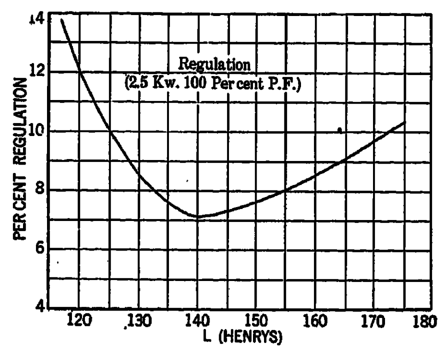


FIG. 6—CURVE OF REGULATION *vs.* INDUCTANCE OF REACTOR

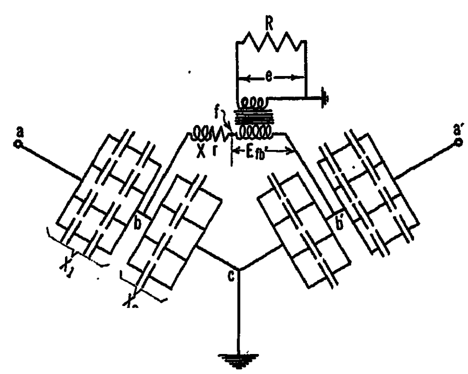


FIG. 7—COMPLETE CIRCUIT OF EQUIPMENT SHOWN IN FIG. 4

direct to the transmission line, however, the operating companies will probably use disconnecting switches. As this type of equipment can be mounted suspended above ground, it will not be necessary to build any enclosing fence as is required for equipment mounted on the ground.

APPLICATION

A study of the various possible circuits has definitely shown that the capacitap may be well adapted to certain classes of loads, while for others, the operation

would be greatly unsatisfactory. For example, either the supply of power to a beacon lamp load or the supply for charging a storage battery through a rectifier would be a satisfactory load; however, the operation of a large motor, or the closing of a circuit breaker would not be suitable. A current surge as encountered in starting a motor should not be delivered by the capacitor power supply as at present designed. Reference to Fig. 9 will show that as the load current increases, the voltage in various parts of the circuit rises, and in

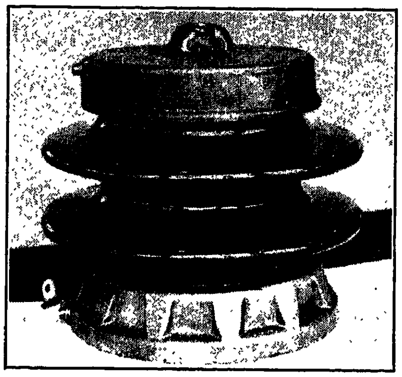


FIG. 8—SINGLE SUSPENSION CAPACITOR UNIT

all places the maximum voltage must not exceed the rating for which each part is designed. The reactor used in the equipment built for study was designed for 14,000 volts; therefore, from curves of Fig. 9 it will be seen that the load must not exceed 2,700 watts. Also an overload will cause a current which may saturate the reactor. This condition would then tend to limit the voltage rise on the capacitor. The spark gaps were installed to protect the circuit from excessive voltage rises.

The capacitap and the transformer both supply low-voltage power from a high-voltage line and there are many things to be considered when choosing between them for any particular application. In general, where less than 3 kw. are required, the transformer will be better adapted to the lower voltage systems, whereas the capacitap is better adapted to the higher voltage systems. The dividing line between a high-voltage and low-voltage system is rather indefinite and will depend somewhat on the applications. For example, the supply of 2 kw. from a 44,000-volt line (25,400 volts to ground) will be best obtained from a transformer, while the supply of 100 watts at 110 volts for charging a storage battery (through a rectifier) may be economically obtained with the capacitap. For all ratings, the efficiency of the transformers and capacitaps is very high at full load, whereas a 50-kv-a. transformer (high voltage) used to supply 2 kw. will be much less efficient.

There are so many variable factors in the design of a capacitap, that all study has been limited to a grounded neutral system. Other arrangements will likely follow which will be adaptable to ungrounded or delta-connected systems.

Single-phase power may be obtained from the use of a line-to-ground connection, (Fig. 2) or a double line-to-ground connection, (Fig. 7). Often one may be considered as a substitute for the other, however, the inherent characteristics of each will greatly affect the choice. As will be shown later, the double line-to-ground circuit has a ground current which is constant and independent of load; however, the single line-to-ground circuit has a ground current which increases with load. If the ground current should become an important factor, especially in the vicinity of telephone circuits, it would be necessary to consider the use of the double line-to-ground circuit instead of the single line-to-ground circuit.

Another factor which should always be considered is that of voltage regulation. The better the regulation required, the larger and more expensive the equipment will become. The regulation is a function of the total kv-a. of capacitors and the ratio between the impedance of the line and ground branches of the circuit. The single line-to-ground circuit will be found to have slightly better regulation than the double line-to-ground circuit, using the same capacitors in either circuit.

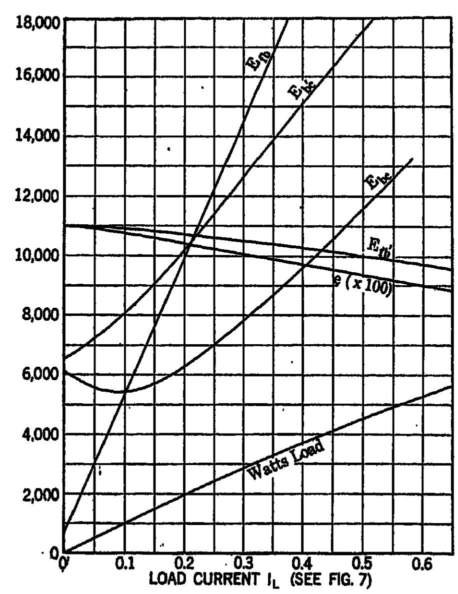


FIG. 9—LOAD AND VOLTAGE CHARACTERISTICS

SUMMARY

The capacitor power supply (capacitap) is an assembly of capacitors and associated apparatus which supplies power at a reduced voltage from high-voltage lines. The present practical limit is 3 to 5 kw. Tests have shown that such an equipment has characteristics which are suitable for only certain types of loads, such as airway beacons. The capacitors are very reliable and are designed with large factors of safety. The equipment may be suspended above ground making an

enclosing fence unnecessary. Two single-phase circuits are possible each having different characteristics with regard to ground current and voltage regulation. Only applications to grounded neutral systems have been considered. The capacitap is especially adapted to high-voltage systems.

The condenser bushing potential device as developed by Mr. J. F. Peters, supplied the basis for development of the capacitor power supply. The author wishes to acknowledge with thanks, the cooperation of Mr. Peters in this present development.

Appendix I

Since the regulation of any standard transformer is known, the characteristics of the circuits may be studied more conveniently by omitting the transformer and using the circuit of Fig. 1.

Let E = line-to-ground voltage.
x_1 = reactance of the upper capacitor group.
x_2 = reactance of the lower capacitor group.
x = reactance of the reactor.
r = resistance of the reactor.
R = load resistance.
X = load reactance.
e = load voltage.
e_0 = no load voltage.
y_2 = admittance of capacitor.
y_L = admittance of reactor-load circuit.

Referring to Fig. 1.

$$y_2 = \frac{1}{-j\,x_2}$$

$$y_L = \frac{1}{(r+R)+j\,(X+x)}$$

$$y_{bc} = \frac{x_2 + j\,[(r+R)+j\,(X+x)]}{x_2\,[(r+R)+j\,(X+x)]}$$

$$= \frac{(x_2 - X - x) + j\,(r+R)}{x_2\,[(r+R)+j\,(X+x)]}$$

$$Z_{bc} = \frac{x_2\,[(r+R)+j\,(X+x)]}{(x_2 - X - x) + j\,(r+R)}$$

$$Z_{ac} = \frac{x_2(r+R)+j\ \ x_2(X+x)-j\ \ x_1(x_2-X-x)+x_1(r+R)}{(x_2 - x - X) + j\,(r+R)}$$

$$= \frac{(x_1+x_2)\,(r+R)+j\,[(x_1+x_2)\,(X+x)-x_1\,x_2]}{x_2 - (X+x) + j\,(r+R)}$$

$$\bar{I}_a = \frac{\bar{E}\,[x_2 - (X+x) + j\,(r+R)]}{(x_1+x_2)\,(r+R)+j\,[(x_1+x_2)\,(X+x)-x_1\,x_2]}$$

$$\bar{I}_L = \frac{\bar{I}_a\,Z_{bc}}{(r+R)+j\,(x+X)}$$

$$\bar{I}_L = \frac{\bar{E}\,x_2}{(x_1+x_2)\,(r+R)+j\,[(x_1+x_2)\,(X+x)-x_1\,x_2]}$$

$$= \frac{\bar{E}}{\dfrac{x_1+x_2}{x_2}\left[(r+R)+j\,(X+x)-j\,\dfrac{x_1\,x_2}{x_1+x_2}\right]}$$

$$e = \frac{\bar{E}\,(R+j\,X)}{\dfrac{x_1+x_2}{x_2}\left[(r+R)+j\,(X+x)-j\,\dfrac{x_1\,x_2}{x_1+x_2}\right]} \tag{1}$$

If a non-inductive load is considered, $X = 0$

$$\bar{e} = \frac{\bar{E}}{\dfrac{x_1+x_2}{R\,x_2}\left[(r+R)+j\left(x-\dfrac{x_1\,x_2}{x_1+x_2}\right)\right]} \tag{2}$$

If x is chosen to make the value of e a maximum, thus securing best regulation,

$$x = \frac{x_1\,x_2}{x_1+x_2}$$

$$\bar{e} = \frac{\bar{E}}{\dfrac{x_1+x_2}{x_2}\left(\dfrac{r}{R}+1\right)} \tag{3}$$

If a reactor could be made with $r = 0$, perfect regulation would be obtained,

$$\bar{e} = \frac{\bar{E}\,x_2}{x_1+x_2} \tag{4}$$

The ground current or line current using equation (1) will be

$$\bar{I}_g = \bar{I}_a = \frac{\bar{E}\,[x_2-(X+x)+j\,(r+R)]}{(x_1+x_2)\,(r+R)+j\,[(x_1+x_2)\,(X+x)-x_1\,x_2]}$$

Considering $X = 0$ and $x = \dfrac{x_1\,x_2}{x_1+x_2}$

$$\bar{I}_g = \frac{\bar{E}\left[\left(x_2 - \dfrac{x_1\,x_2}{x_1+x_2} + j\,(r+R)\right)\right]}{(x_1+x_2)\,(r+R)}$$

$$\bar{I}_g = \bar{E}\left[\frac{x_2^2}{(x_1+x_2)^2\,(r+R)} + j\,\frac{1}{x_1+x_2}\right] \tag{6}$$

It is interesting to note that for $R = \infty$ (no load)

$$\bar{I}_g = \frac{j\,\bar{E}}{x_1+x_2}$$

Appendix II

A similar analysis of the double line-to-ground circuit as shown in Fig. 3 follows:

Let

$\bar{E}_{ca} = E\,(-0.5 + j\,0.866)$

$\bar{E}_{ca'} = E$

$\bar{E}_{ca} = -j\,x_2\,(\bar{I}_{ab} - \bar{I}_L) - J\,x_1\,\bar{I}_{ab}$

$$\bar{E}_{ca} = -j\,(x_2 + x_1)\,\bar{I}_{ab} + j\,x_2\,\bar{I}_L \tag{1}$$

$$\bar{E}_{ca'} = -j\,x_2\,(\bar{I}_{a'b'} + \bar{I}_L) - j\,x_1\,\bar{I}_{a'b'} \tag{2}$$

$$o = -j\,x_2\,(\bar{I}_{ab} - \bar{I}_L) - [(r + R) + j\,(x + X)]\,\bar{I}_L + j\,x_2\,(\bar{I}_{a'b'} + \bar{I}_L) \tag{3}$$

Solving equations (1), (2), and (3) simultaneously for $\bar{I}_L$

$$\bar{I}_L = \frac{E\,(1.5 - j\,0.866)}{-\left(\dfrac{x_1 + x_2}{x_2}\right)(r+R) + j\left[2\,x_1 - \left(\dfrac{x_1 + x_2}{x_2}\right)(x+X)\right]} \tag{4}$$

$$\bar{e} = \frac{E\,(1.5 - j\,0.866)\,(R + j\,X)}{-\left(\dfrac{x_1 + x_2}{x_2}\right)(r+R) + j\left[2\,x_1 - \left(\dfrac{x_1 + x_2}{x_2}\right)(x+X)\right]} \tag{5}$$

$$\bar{I}_{ab} = \frac{E + j\,x_2\,\bar{I}_L}{-j\,(x_1 + x_2)} \tag{6}$$

$$\bar{I}_{a'b'} = \frac{E\,(-0.5 + j\,0.866) - j\,x_2\,\bar{I}_L}{-j\,(x_1 + x_2)} \tag{7}$$

$$\bar{I}_g = \bar{I}_{ab} + \bar{I}_{a'b'} = \frac{E\,(0.5 + j\,0.866)}{-j\,(x_1 + x_2)} \tag{8}$$

Assuming a load having only resistance then $X = o$ and equation (5) becomes

$$\bar{e} = \frac{E\,(1.5 - j\,0.866)\,R}{-\left(\dfrac{x_1 + x_2}{x_2}\right)(r+R) + j\left[2\,x_1 - \left(\dfrac{x_1 + x_2}{x_2}\right)(x)\right]} \tag{9}$$

let $x = \dfrac{2\,x_1\,x_2}{x_1 + x_2}$ then $\dfrac{(x_1 + x_2)}{(x_2)}\,x = 2\,x_1$

$$\bar{e} = \frac{E\,(1.5 - j\,0.866)}{-\left(\dfrac{x_1 + x_2}{x_2\,R}\right)(r + R)} \tag{10}$$

Not only does this expression give conditions for best voltage regulation, but also the voltage $\bar{e}$ is in phase with $\bar{V}_{aa'}$.

Experiences with Grounded-Neutral, Y-Connected Potential Transformers on Ungrounded Systems

BY C. T. WELLER[1]

Member, A. I. E. E.

Synopsis.—The application of Y-connected transformers to three-phase, three-wire systems, in such a manner that the third and its multiple harmonics of the exciting currents would ordinarily be suppressed, is not in accordance with the best practise. However, such applications of grounded-neutral, Y-connected potential transformers, particularly to temporarily ungrounded systems, have been made for relaying and other purposes. The resulting complications, which are of a different nature than would be anticipated from the suppression of the third and its multiple harmonics may not be generally appreciated, so this paper outlines experiences with two such applications. The peculiar and dangerous "saturation phenomena" obtained and the methods of preventing their occurrence are described and considerable data thereon included. The phenomena are discussed from theoretical standpoints in companion papers by A. Boyajian and O. P. McCarty and by C. W. La Pierre.

INTRODUCTION

THE application of Y-connected transformers to three-phase, three-wire systems, in such a manner that the third and its multiple harmonics of the exciting currents would ordinarily be suppressed, is generally regarded as objectionable. For power transformers, this difficulty has been overcome (1) by connecting the secondaries in delta or, if that is not permissible, (2) by adding tertiary windings connected in delta or (3) by adding a fourth conductor (metallic or ground) to connect the transformer and system neutrals. For potential transformers, only method (3) can usually be considered, since the closed-delta secondary or tertiary connection of methods (1) or (2) makes possible comparatively large circulating currents under certain system conditions. Potential transformer applications that do not utilize method (3), therefore, are not in accordance with the best practise for power transformers; however, applications of this nature have been made.

Grounded-neutral, Y-connected potential transformers with Y- or "broken-delta"-connected secondaries have been applied to three-phase, three-wire systems, the neutrals of which are temporarily or permanently ungrounded. The purposes of such applications include the protection of equipment against grounds, the economy resulting from the use of line-to-neutral[2] (L/N) instead of line-to-line[2] (L/L) potential transformers and the maintenance of the isolated-phase scheme for such installations.

It may not be generally appreciated that such applications frequently endanger connected equipment in addition to creating special relaying, synchronizing, and metering problems. This paper, therefore, outlines experiences with two applications under actual operating conditions which illustrate the inherent danger and afford a basis for the "General Recommendations" made. The paper is written from the operating standpoint, so the pertinent relaying and synchronizing problems are discussed briefly under "Significance of Results;" the metering problems, which involve questions of accuracy rather than of operation, are not discussed.

One of the systems operates at 12 kv., 60 cycles and

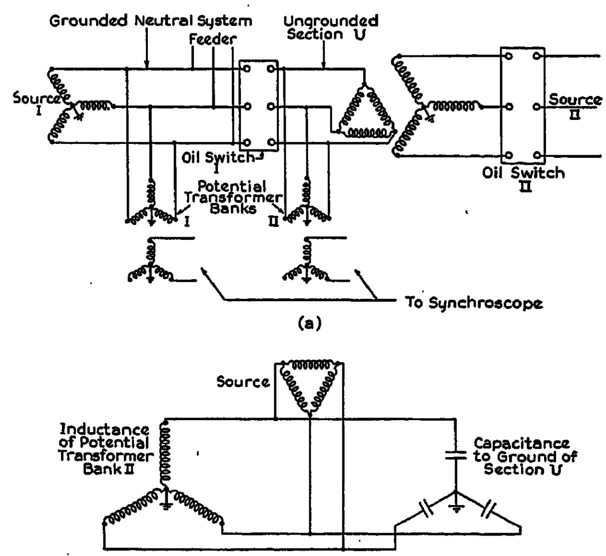


FIG. 1—SCHEMATIC DIAGRAMS

a. Typical system connections
b. Elements of circuit U

the other operates at 110 kv., 25 cycles. Each system is grounded at one point only, so sections separated temporarily from the system are, in general, ungrounded. The fact that the neutrals of the potential transformers connected to these sections are grounded does not change their designation as ungrounded sections or systems. The peculiar and dangerous phenomena to be described occurred when voltage was applied suddenly to ungrounded sections of the systems. This condition is indicated in Fig. 1a, when *Oil Switch I*

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2. The abbreviations L/L for "line-to-line" and L/N for "line-to-neutral" are used throughout the paper.

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is open and voltage is applied to *Ungrounded Section U* from *Source II* by closing *Oil Switch II*.

The principal factors involved are the capacitance to ground of the immediate circuit, the inductance of the potential transformers and the point on the saturation curve at which the potential transformers normally operate; the first two factors are represented in Fig. 1b, but the third factor, although not represented, is most important, as the phenomena are fundamentally "saturation phenomena."[3]

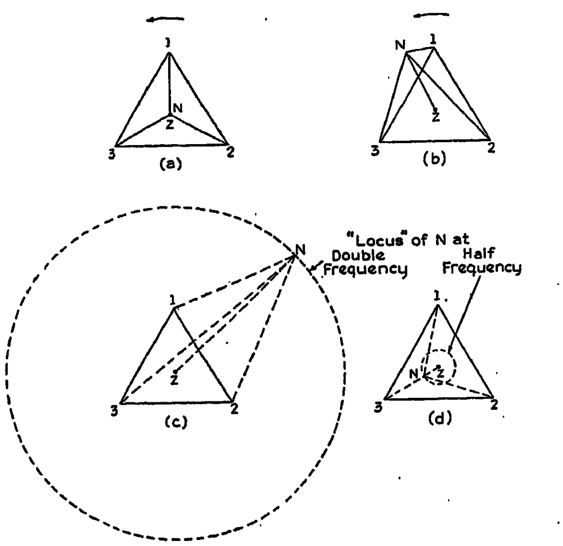


FIG. 2—REPRESENTATIONS OF VOLTAGE PHENOMENA BY MEANS OF VECTORS

a. Normal condition. Neutral N coincides with center of gravity Z of delta voltage triangle 1-2-3
b. Phenomenon A. Neutral N located near one vertex of delta voltage triangle 1-2-3
c. Phenomenon B. Neutral N oscillates at double frequency ouside of delta-voltage triangle 1-2-3
d. Phenomenon C. Neutral N oscillates at half frequency inside of delta-voltage triangle 1-2-3

The potential transformers were designed for normal operation at L/N voltage and for emergency (two-hour) operation at L/L voltage. Temporary operation in case of a ground on one line of the ungrounded section, which would apply L/L voltage to two of the potential transformers, was thus provided for; their ratings are given in Table I.

TABLE I
RATING OF POTENTIAL TRANSFORMERS

Cycles	Volt-amperes	Volts	
		Operating (L/N)	Circuit (L/L)
60	200	7,200:120	12,000
25	1000	63,500:63.5	110,000

SUMMARY OF RESULTS

The peculiar and dangerous saturation phenomena described briefly here were obtained frequently when voltage was applied to grounded-neutral, Y-connected potential transformers on temporarily ungrounded systems by closing an oil switch; at other times, the anticipated normal results, consisting of balanced L/N voltages equal to approximately 58 per cent of the applied L/L voltages, were obtained under the same system conditions. Connections are indicated in Figs. 1a and 3. The phenomena will be considered under three classifications, A, B and C (a fourth classification, D, covers a somewhat special case).

Phenomenon A consists of a displacement of the neutral (or ground) of the potential transformers from its normal position at the center of gravity of the delta-voltage triangle to a position near any vertex; the displaced neutral may be either inside, on the edge or outside of the triangle. Approximate L/L voltage then appears on two of the potential transformers, while a small voltage of very distorted wave shape appears on the third potential transformer. The normal voltage condition is indicated in Fig. 2a; one aspect of Phenomenon A is represented in Fig. 2b.

Phenomenon A occurred frequently under some conditions but not at all under other conditions on both the 12- and the 110-kv. systems. Representative secondary voltmeter readings obtained are given in Tables II and III, while the three L/N voltages are shown in Figs. 4 and 7 (last two cycles in Fig. 7).

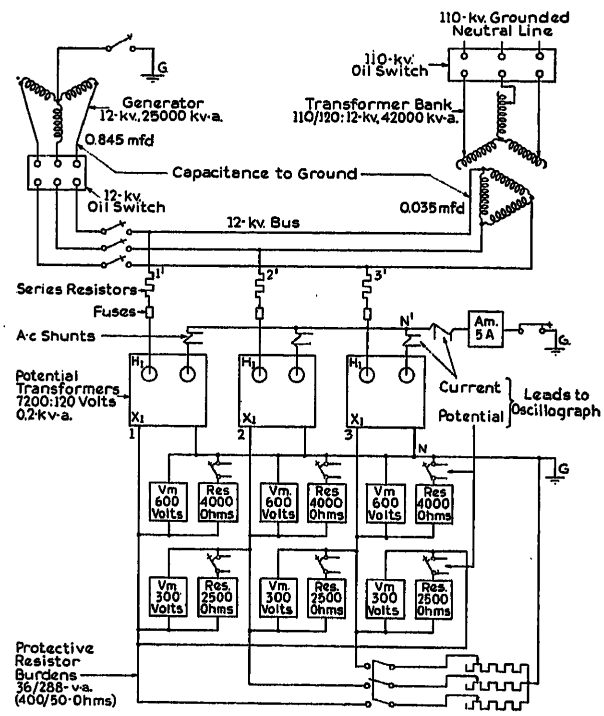


FIG. 3—SCHEMATIC DIAGRAM OF CONNECTIONS FOR TESTS ON 12-KV., 60-CYCLE SYSTEM

Phenomenon B consists of an oscillation at double frequency of the neutral (or ground) of the potential transformers outside of the delta-voltage triangle. Equal or balanced voltages of unsymmetrical wave shape and about 2.7 times normal magnitude appear

3. For discussions from theoretical standpoints, see following papers, *Physical Nature of Neutral Instability*, by A. Boyajian and O. P. McCarty, and *Theory of Abnormal Line-to-Neutral Transformer Voltages*, by C. W. LaPierre.

on the three potential transformers. These voltages are accompanied by balanced exciting currents of sharply peaked wave shape and about 10 times rated full-load current in magnitude; operation well up on

TABLE II
12-KV., 60-CYCLE SYSTEM
7.2-KV. POTENTIAL TRANSFORMERS
COMPARISON OF PHENOMENA *A*, *B*, AND *C* WITH NORMAL SECONDARY VOLTMETER READINGS
(Approximate Primary Volts = Tabulated Volts × 60)

	Line-to-line (L/L)			Line-to-neutral (L/N)			
Per cent*	1-2	2-3	3-1	1-N	2-N	3-N	Phenomenon
	Capacitance to ground of 12-kv. circuit, 0.035 μf						
94	194.6	194	196.5	113	115	111	..
94	194.2	194	195.2	195	†	180	*A*
100	206	206.5	206.8	195	†	183	*A*
100	206.5	206	207.4	†	174	194	*A*
100	206.5	206.5	208	187	187	†	*A*
104	215.2	215	218	125	126	122	..
104	213.4	212.8	215.4	194	†	180	*A*
104	215.8	214	217.6	123	125	122	..
104‡	209	207.6	211.5	334.5	331.5	336	*B*
	Capacitance to ground of 12-kv. circuit, 0.845 μf.						
100	207	208	209.2	120	119	122	..
100‡	197.5	199	200	147	148	149	*C*
113	233.5	235	234.8	134	133	138	..
113‡	224	225	227	155	155	155	*C*

*Approximate—based on potential transformer rating of 208 volts L/L ($= 1.73 \times 120$ volts L/N).
†Volts too low to read on 600-volt voltmeter.
‡Supply voltage practically unchanged from previous reading.

the saturation curve is indicated thereby. Distinctly audible beats occur with a frequency of from about 30 to 170 per minute; excessive corona also occurs. Phenomenon *B* is represented in Fig. 2c.

Phenomenon *B* started frequently under some con-

TABLE III
110-KV., 25-CYCLE SYSTEM
63.5-KV. POTENTIAL TRANSFORMERS
COMPARISON OF PHENOMENON *A* WITH NORMAL SECONDARY VOLTMETER READINGS
(Approximate Primary Volts = Tabulated Volts × 1000)

	Line-to-line (L/L)			Line-to-neutral (L/N)			
Per cent*	1-2	2-3	3-1	1-N	2-N	3-N	Phenomenon
100‡	110.3	111.8	109.5	64.1	64.2	64	..
110	122.7	123.8	121.4	70.4	71.3	70.5	..
110	119	121.8	119.2	138.2	22†	129.8	*A*
	Duplicate bank of potential transformers added						
100	110.2	111.9	109.8	63.5	64	63	..
100	110	110.5	108.3	16†	113.8	122.5	*A*
110	122.2	123.2	122	70.3	71.2	70	..
110	121.5	121.7	120.8	13†	114.3	121	*A*

*Approximate—based on potential transformer rating of 110 volts L/L ($= 1.73 \times 63.5$ volts L/N).
†Estimated value.
‡Phenomenon *A* not obtainable.

ditions but held long enough to take instrument readings only at rated L/L voltage or higher on the 12-kv. system and even then only at certain times. Representative voltmeter readings are given in Table II; as compared with the normal condition, a drop of about 3 per cent in the indicated L/L voltages during *B* is noticeable; this is evidently caused by the excessive exciting currents. The three L/N voltages are shown in Fig. 5a for the 12-kv. system and in Fig. 7 (part of one cycle) for the 110-kv. system. Fig. 5b shows the voltages 2-N and 3-2 and the primary

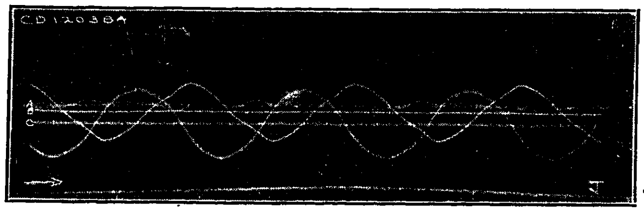
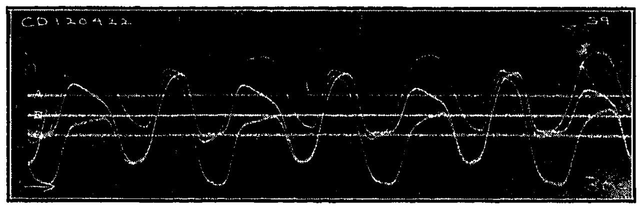


FIG. 4—7.2-KV. POTENTIAL TRANSFORMERS—PHENOMENON A
(SEE FIG. 3 FOR CONNECTIONS)

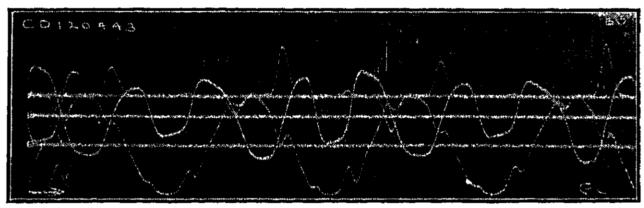
Curve A, voltage 2-N
Curve B, voltage 3-N
Curve C, voltage N-1

current in line 2′ on the 12-kv. system; the double-frequency current from the primary neutral N' to ground G was about 0.58 ampere.

Phenomenon *C* consists of an oscillation at half frequency of the neutral (or ground) of the potential transformers inside of the delta-voltage triangle. Equal or balanced voltages of unsymmetrical wave shape and about 1.2 times normal magnitude appear on the three potential transformers. These voltages are accompanied by balanced exciting currents of sharply peaked wave shape and about 15 times rated full-load current in magnitude; operation at a point on the saturation curve well beyond that for Phenome-



a. Curve A, voltage 3-N
Curve B, voltage 2-N
Curve C, voltage 1-N



b. Curve A, current line 2′
Curve B, voltage 2-N
Curve C, voltage 3-2

FIG. 5—7.2-KV. POTENTIAL TRANSFORMERS—PHENOMENON B

non *B* is indicated thereby. Distinctly audible beats occur with a frequency of about 240 per minute. Phenomenon *C* is represented in Fig. 2d.

Phenomenon *C* occurred frequently under one condition only on the 12-kv. system. Representative voltmeter readings are given in Table II; as compared

with the normal condition, a drop of about 4 per cent in the indicated L/L voltages during C is noticeable; this is evidently caused by the excessive exciting currents. Fig. 6 shows the voltages 3-N and 1-3 and the primary current in line 3'; the half-frequency current

FIG. 6—7.2-KV. POTENTIAL TRANSFORMERS–PHENOMENON C

Curve A, voltage 3-N
Curve B, current line 3'
Curve C, voltage 1-3

from the primary neutral N' to ground G was about 0.88 ampere.

The occurrence of Phenomena A, B, and C, as shown by sustained instrument readings, was prevented in all cases by adding sufficient secondary burdens of resistance. The values (at 120 volts) of the protective resistor burdens required on the 12-kv. system are as follows: Phenomenon A, at all voltages tried, 72-volt-amperes; Phenomenon B, about 20 volt-amperes; Phenomenon C at rated L/L voltage, 72 volt-amperes—a burden of 72 volt-amperes, therefore, was provided for each transformer. Similarly, the burden values (at 63.5 volts) required on the 110-kv. system are: Phenomenon A (and B), at all voltages tried, 900 volt-amperes per transformer with one bank of potential transformers or 600 volt-amperes per transformer with two banks of potential transformers.

Results similar to those just described were obtained on the 12-kv. system, when other potential transformers of the same rating were substituted for the first group tried.

In further tests made on the 12-kv. system (capacitance to ground 0.035 μf.), Phenomena A and B also occurred when a bank of 13.2-kv. potential transformers was connected in multiple with the bank of 7.2-kv. transformers; however, neither A nor B occurred when the 7.2 kv. bank was disconnected.

Phenomenon B occurred when a bank of 6.9-kv., 1.5-kv-a. distribution transformers was connected in alone. A different phenomenon (D) occurred when the 5.96-kv. tap on this bank was used (this tap, of course, would not be used in practise on a 7.2-kv. circuit). Phenomenon D consists of an oscillation at triple frequency of the neutral (or ground) outside of the delta-voltage triangle; equal or balanced voltages of about 3.5 times normal appear on the three transformers; audible "buzzing" and excessive corona occur. Phenomenon D did not hold long enough at any time to obtain a complete set of instrument readings; evidently D is easier to prevent than B.

SIGNIFICANCE OF RESULTS

Phenomena A, B, and C and the conditions under which they occur are not characteristic of any particular ungrounded system or type of transformer. Phenomena B and C endanger the potential transformers themselves; the former also endangers other connected equipment. All three phenomena tend to cause incorrect synchronizing and incorrect relay operation; the difficulties depend to some extent on the secondary connections used.

Y-Connected Secondaries. Ordinarily, if any one of the L/N voltages should be chosen for synchronizing purposes, it is evident that the indications frequently obtained would be considerably in error both in magnitude and in phase position, to say nothing of wave shape and frequency. This particular difficulty could be readily overcome by using any one of the L/L voltages. However, the correct effective secondary values would not be indicated by the voltmeters for Phenomena B or C, although this error would be small (see Table II); also, there might be some disturbance caused by throwing together two systems, one of which was being subjected to Phenomena A, B or C.

Broken-Delta-Connected Secondaries. Ordinarily, the high-impedance "ground relay" connected across the broken delta would operate frequently, although no accidental ground existed on the system.

These difficulties can be overcome in various ways such as by grounding the sections of the system, by using the L/L connection for all potential transformers, by providing protective resistor burdens for L/N rated potential transformers or by using potential transformers of considerably higher than L/N-voltage ratings for the L/N connection, and thereby lowering

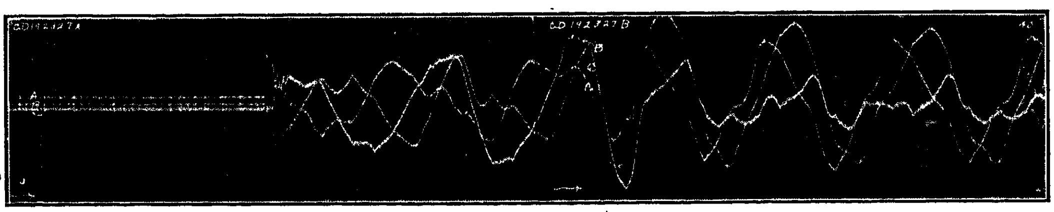


FIG. 7—SIX 63.5-KV. POTENTIAL TRANSFORMERS (TWO Y-BANKS)—START OF PHENOMENON A (AND B)

Curve A, voltage 3-N
Curve B, voltage 2-N
Curve C, voltage 1-N

the point on the saturation curve at which the transformers normally operate. The last two methods in particular are amplified under "General Recommendations."

GENERAL RECOMMENDATIONS

These recommendations are intended to serve as a guide in the application of grounded-neutral, Y-connected potential transformers to three-phase, three-wire systems or sections thereof, which are ungrounded temporarily or permanently.

Protective resistor burdens should be used in practically all cases if the occurrence of Phenomena A, B, and C is to be prevented under all possible operating conditions. The approximate relative values of such secondary burdens are given in Table IV; secondary connections are discussed in subsequent paragraphs.

TABLE IV
APPROXIMATE RELATIVE VALUES OF PROTECTIVE RESISTOR BURDENS REQUIRED TO PREVENT OCCURRENCE OF PHENOMENA A, B, AND C

System or section neutral	Y-connected potential transformers: Primary neutral	Normal voltage rating	Relative value of burdens
Ungrounded temporarily	Grounded	L/N	1.0
	Grounded	L/L	0.5
	Grounded	$2 \times L/N$	..
Ungrounded permanently	Grounded	L/N	1.5
	Grounded	L/L	0.75
	Grounded	$2 \times L/N$	0.25

It is always desirable to keep the volt-ampere ratings of the protective resistor burdens as small as possible and this involves a consideration of the characteristics of each proposed installation. The magnitude of the burdens provided for the potential transformers of L/N voltage design on the 12-kv. and 110-kv. systems was determined experimentally and a rough idea of the general requirements was thereby obtained; the magnitude of these burdens constitutes the standard of reference for the relative values in Table IV.

Potential transformers of L/L voltage design without protective burdens were entirely satisfactory on the 12-kv. system from the standpoint of non-occurrence of the phenomena described. Transformers of similar design without protective burdens have been recommended, therefore, for similar service and so far as is known, have also proved entirely satisfactory from that standpoint wherever installed. However, theoretical considerations and laboratory tests indicate that the phenomena may occur under favorable conditions if standard potential transformers are normally operated at approximately 58 per cent of rated voltage, as in the above cases, but not if operated at or below 50 per cent of rated voltage; these values depend, of course, on the actual flux densities involved. Protective burdens are recommended, therefore, for transformers of L/L voltage design; the ratio between the volt-ampere ratings of the burdens for transformers of L/L and L/N voltage design, respectively, is about 0.5 to 1; small burdens are recommended for transformers of twice L/N-voltage design.

A differentiation is made in Table IV between temporarily and permanently ungrounded systems. The ratio of the volt-ampere ratings of the protective burdens recommended for the two conditions is about 1 to 1.5. It is believed that a greater margin of safety is desirable for permanently ungrounded systems, since they are always subject to disturbances tending to displace the neutral from its normal position; installations of potential transformers on such systems have not been investigated.

In order to make this section more complete, two general cases involving Y-connected potential transformers, but somewhat outside the scope of the paper, are included. The first is their application with ungrounded or isolated neutral to any three-phase system; in this case, the L/N voltages are of little value for any purpose; further, if the secondaries are Y-connected to permit obtaining L/L voltages, the L/N voltage waves are distorted because of the suppression of the third and its multiple harmonics in the exciting currents, as is well known; such installations are not recommended. The second case occurs when the system and potential transformer neutrals are connected by means of a fourth conductor, as in method (3); this case is covered by standard practise for three-phase, four-wire systems.

Secondary Connections. The protective resistor burdens recommended for potential transformers with grounded primary neutrals must be connected L/N if the secondaries are Y-connected. The Y-connection is recommended when synchronizing is involved in order to permit utilizing the L/L voltage; special considerations apply when metering is involved.

An equivalent burden may be connected across the broken delta, if the secondaries are so connected, when metering is not involved. A similar result may be obtained with Y-connected secondaries by utilizing a small Y-broken-delta-connected auxiliary transformer bank to supply the equivalent burden; four conductors must be used to connect the potential and auxiliary transformer banks.

The closed-delta secondary connection should not be used when the primary neutral is grounded, since a ground on any line of the system would undoubtedly cause sufficient circulating current to destroy the transformers.

The secondary neutral (preferably), if Y-connected, or one line, if broken-delta-connected, should always be grounded in accordance with standard practise.

Methods of Test

12-Kv., 60-Cycle System

(1) OPERATION OF POTENTIAL TRANSFORMERS

(a) *Supplied from 42,000-Kv-a. Transformer Bank.* Connections are indicated in Fig. 3. Tests were made

with the three bus-disconnect switches open; the 12-kv. oil switch was open also. Voltage was applied to the 12-kv. bus and the bank (*s*) of potential transformers by means of the 110-kv. oil switch; this switch was closed (and opened) more than 600 times during the tests.

Voltage control of the 110-kv. circuit was not available so the usual variations in voltage occurred. Two bus voltages differing by about 9 per cent were obtained by means of taps on the high-voltage windings of the three-unit power transformer bank; the ratings used were 120 to 12 and 110 to 12 kv., respectively. The phase rotation of the 12-kv. circuit was 1′-2′-3′.

A 60-ohm series resistor and a fuse were connected in the primary circuit of each 7.2-kv. potential transformer. The neutral N' was isolated, when desired, by opening the switch between N' and ground G.

The current from N' to G was read on the 5-ampere ammeter (if of sufficient magnitude) and its wave shape was determined with the oscillograph (not shown) by taking the voltage drop across the adjacent a-c. shunt. Similarly, the wave shapes of the currents in primary lines 1′, 2′ and 3′ were determined from the voltage drops across the respective shunts next to N'; the drop leads are labelled "current."

One 30-kv. electrostatic voltmeter (not shown) was connected between lines 1′, 2′ or 3′ and ground to check roughly the secondary L/N voltmeters. Except for this voltmeter, all instruments used were of the portable type.

The secondary L/N voltages 1-N, 2-N, and 3-N were read on 600-volt voltmeters (lowest scale point, 100 volts); the L/L voltages 1-2, 2-3, and 3-1 were read on 300-volt voltmeters (lowest scale point, 40 volts). The wave shapes of these voltages were determined with the oscillograph; the leads are labelled "potential." In most cases, series resistances of 4,000 ohms each for the three L/N voltages and of 2,500 ohms each for the three L/L voltages were used; the small series switches shown were open when taking oscillograms of the respective voltages and closed at other times in order to keep the minimum burdens constant. Each minimum burden thus consisted of two parts, one of about 4 volt-amperes actual L/N and the other of about 29 volt-amperes L/L or equivalent L/N, both values being in terms of 120 volts.

The lowest resistance tap on the L/N oscillograph resistors that could be used even temporarily up to 350 volts was 1,000 ohms; this constituted a nominal burden of about 15 volt-amperes at 120 volts. Larger burdens were obtained with the protective resistors, which could be connected to give either 36, 72, 144 or 288 volt-amperes (400, 200, 100 or 50 ohms, respectively). These burdens were sometimes connected equivalent L/N by isolating their neutral; single burdens were sometimes connected L/L.

The general procedure in preventing the occurrence of the phenomena was to determine the amount of burden necessary on each transformer to reduce any particular existing phenomenon to normal. Starting with a small burden, successively larger burdens were connected until reduction to normal took place. The correctness of the burden value so determined was checked by applying the three equal burdens by means of the three-pole switch during several subsequent occurrences of the phenomenon. It was found that the phenomenon would not occur if the oil switch were closed with such burdens or somewhat smaller ones connected. The significant value was that necessary to prevent the occurrence of the most obstinate phenomenon. An approximation was sometimes obtained by connecting one burden L/N. Also, Phenomenon A could be obtained from normal by adding a single burden of 288 volt-amperes to any one of the three 7.2-kv. transformers, when otherwise supplying voltmeters (and oscillograph resistors) only.

Many sets of instrument readings and oscillograms were taken in order to cover adequately all phenomena encountered or produced, with particular emphasis on those associated with actual or possible operating conditions. For each set of readings, the instruments were read as quickly as possible, so as to obtain comparable values. Accurate instrument corrections were not available but the approximate corrections did not exceed two per cent, so no corrections were applied. For the oscillograms, 12-in. films were generally used at fairly high speed for stable conditions and 48-in. films at a somewhat slower speed for starting or transient conditions. Calibrations were taken for each set of oscillograms.

(*b*) *Supplied from 25,000-Kv-a. Generator*. Connections are indicated in Fig. 3. The tests were made with the generator ground, the three disconnect and the 110-kv. switches open. The potential transformers were connected between the disconnect and 12-kv. switches for this test only. Voltage was applied by means of the 12-kv. oil switch. Generator field control was available, so the test voltage range was somewhat wider than for (*a*). The generator voltage was set approximately by the field ammeter before closing the 12-kv. switch. Instrument readings and oscillograms were taken and protective burdens were tried as described under (*a*).

(2) DETERMINATION OF CAPACITANCE TO GROUND

System connections are indicated in Fig. 3. The capacitance to ground of the 12-kv. bus and connected equipment was determined by the volt-ampere method. Voltage was applied to the generator lines by means of a high-potential testing set excited from a separate source. A 13,200 to 110-volt potential transformer and a 150-volt voltmeter were used to determine the applied voltage. The charging current was read on a 5-ampere ammeter, which was connected in the grounded line. Readings were taken (*a*) with the generator and potential transformer ground and 110-kv. switches open and

the bus-disconnect and 12-kv. switches closed and (*b*) with the bus-disconnect switches open.

The capacitance of the transformers and bus to ground equals the difference between the results of tests (*a*) and (*b*).

In view of the fact that the capacitance value so obtained (0.035 μf.) was relatively small, a check test was made by using one of the 7.2-kv. potential transformers as a step-up transformer, the other two potential transformers being disconnected from ground. The applied voltage was determined by multiplying the secondary voltmeter reading by the nominal transformer ratio. The charging current was determined with the oscillograph by taking the drop across a shunt connected in the grounded line. Readings were taken with the bus-disconnect and 110-kv. switches open.

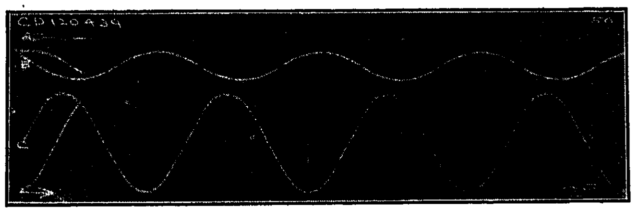
110-Kv., 25-Cycle System

Operation of Potential Transformers

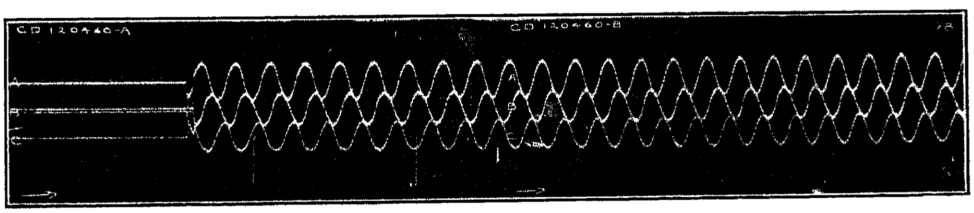
The set-up was similar to that indicated in Fig. 1a with *Oil Switch I* open and voltage applied to *Potential Transformer Bank II* from *Source II* by closing *Oil Switch II*. Field control of the *Source II* generator (it and its transformer bank not shown) was available. Tests were made with one bank of 63.5-kv. potential transformers and also with two 63.5-kv. banks in multiple, one bank being connected Y-Y and the other bank Y-broken delta.

Two expedients were resorted to in order to obtain the desired number of operations without using the oil switch. First, a three-pole, air-break disconnect switch was inserted between the power and potential transformers, and voltage applied to the latter thereby. Arcing occurred every time just before the switch closed and in every case normal voltages were obtained, which was not the case when using the oil switch. Second, one leg of the Y-connected secondary was short-circuited through a fuse; this generally produced Phenomenon *A*, with the short-circuited phase "low," before the fuse melted.

One end of each potential transformer primary winding was solidly grounded so no current shunts or "neutral ammeter" could be used. Voltmeters (150-volt) were connected L/L and L/N on the secondaries as indicated in Fig. 3 for the Y-Y bank; the ratings of the voltmeters used for the broken-delta bank ranged from 10 to 300 volts. No attempt was made to keep the oscillograph resistors balanced because of the comparatively large transformer rating (1 kv-a). Voltmeter readings and oscillograms were taken and protective resistor burdens were tried as described under (1a); also, single protective resistor burdens were applied to the broken-delta bank by means of a single-pole switch. It was impracticable to determine the capacitance to ground of the immediate circuit because of the solid ground at the neutrals of the potential transformer banks.



a. Curve A, current N'-G
Curve B, voltage 2-N
Curve C, voltage 3-2



b. Start
Curve A, voltage 1-N
Curve B, voltage 2-N
Curve C, voltage 3-N

Fig. 8—7.2-Kv. Potential Transformers—Normal Condition

Detailed Results

Results supplementing those under "Summary" are given in this section; most of the results were obtained on the 12-kv. system. A description of the "Methods of Test" has been given under that title. The designation used for the secondary L/L and L/N voltages and the primary currents refers to the numbers of the corresponding lines in Fig. 3; the phase rotation is 1-2-3. The term *rated voltage* always refers to the voltage rating of the potential transformers under test.

In practically every case, the important features are illustrated by oscillograms. Eighteen of the thirty oscillograms show the start of the several phenomena; seventeen show initial transient voltage oscillations, which occurred at the rate of approximately 3,500 cycles

per sec. on the 12-kv. system. As far as possible, oscillograms showing more than one phenomenon were chosen. Any L/L voltage, when shown, constitutes a timing wave, particularly for Phenomena B, C, and D.

Instrument readings taken in connection with the oscillograms are given in Tables V, VI, VII, and IX; electrostatic voltmeter readings taken directly on the 12-kv. circuit are not included in the first three tables as they checked the corresponding secondary voltmeter readings within expected limits.

12-Kv., 60-Cycle System

(I) OPERATION OF POTENTIAL TRANSFORMERS

(*1*) *Supplied from 42,000-Kv-a. Transformer Bank-Capacitance to Ground of 12-Kv. Circuit, 0.035 μf.*

(a) THREE 7.2-KV. POTENTIAL TRANSFORMERS

Suppression of Third and Multiple Harmonics. Reference was made under "Introduction" to the suppression of the third and its multiple harmonics of the exciting currents, the effects of which are well known, in order to bring out the fact that the installations were not in accordance with the best practise in this respect; also, the phenomena might be attributed to this suppression. Actually, however, the capacitance to ground of the immediate circuit apparently absorbed practically all harmonics in the exciting currents, including the comparatively large harmonics accompanying the approximate saturation of the potential transformer cores.

This is well illustrated for the third harmonics in Fig. 8a, which shows voltages 2-N, 3-2 and current N'-G. The L/N and L/L voltage waves show practically no distortion; the small neutral current is apparently all third harmonic current. Thus the normal L/N voltage readings obtained were practically the same as if taken on a three-phase, four-wire system.

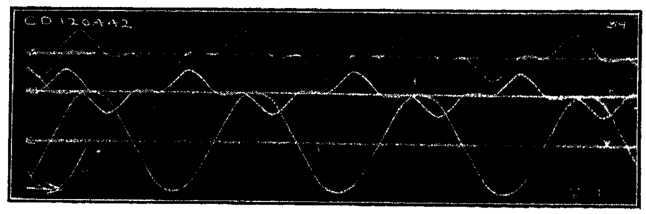
Out of 350 operations of the oil switch with one particular bank of potential transformers over a L/L voltage range of about 5 per cent, 187 (about 54 per cent of total) sets of normal voltage readings were obtained, although perhaps one-third started out as Phenomenon B (q. v.) and a small number as Phenomenon A (q. v.)

The start of the three L/N voltages is shown in Fig. 8b. The start (as Phenomenon A) of voltages 1-N, 2-1 and current 1′ is shown in Fig. 10b; oscillations in the current are not apparent; the normal condition is shown at the right.

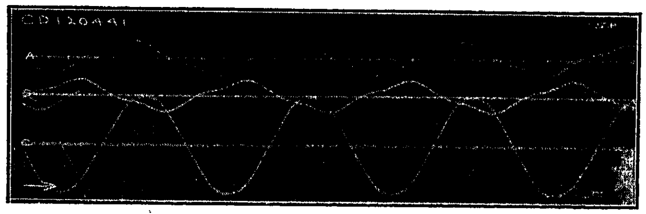
Voltmeter readings taken in connection with all of the figures described in this section (a) are given in Table V; when possible, ammeter readings of the primary neutral-to-ground current N'-G were taken and are included in Table V.

The effect of isolating the primary neutral and thereby actually suppressing the third and its multiple harmonics is clearly shown in Fig. 9a, in which the third harmonic in the two L/N voltage waves is very prominent. In this case, the neutral oscillates at triple frequency inside of the delta-voltage triangle. Fig. 9b shows the same voltages as Fig. 9a, but the L/N wave shapes have been somewhat improved by the addition of resistor burdens of 72 volt-amperes (200 ohms) per transformer.

Phenomenon A. Audible evidences of distress in the potential transformers during the occurrence of Phenomenon A were entirely lacking. It was not possible, therefore, to determine how many operations started out as A and finished otherwise. Out of 350 operations of the oil switch, however, 142 (about 40 per cent of total) sets of A voltage readings were obtained; of these, voltages 1-N, 2-N, and 3-N were too low to read on their respective voltmeters in the approximate ratio of 10 to 60 to 30. Differences in the characteristics of the transformers and (or) in the magnitudes of the three capacitances to ground are doubtless indicated thereby.



a. Curve A, voltage 3-N
Curve B, voltage 2-N
Curve C, voltage 3-2



b. 72-v-a.—resistor burdens
Curve A, voltage 3-N
Curve B, voltage 2-N
Curve C, voltage 3-2

FIG. 9—7.2-KV. POTENTIAL TRANSFORMERS—THIRD HARMONIC PHENOMENON

The three L/N voltages are shown in Fig. 4, voltage 2-N being low; the start of these voltages is shown in Fig. 10a. The start of voltages 1-N, 2-1 and current 1′ (crest value about 0.17 ampere when symmetrical) is shown in Fig. 10b; the relation between voltage 1-N and current 1′ is clearly shown near the center, one current peak coinciding approximately with each zero-voltage point; A quickly relapsed into normal. The start of voltages 3-2, 2-1 and current N'-G is shown in Fig. 10c. Current N'-G, which has a distorted wave shape (crest value about 0.42 ampere at start, 0.17 ampere subsequently), is absorbed by the circuit capacitance; the stability of A is indicated by the unvarying wave shapes at the right; the distortion of the L/L voltage waves is apparently negligible, as would be expected from the fact that the exciting currents are comparatively small. The three primary line currents

TABLE V

12-KV., 60-CYCLE SYSTEM. CAPACITANCE TO GROUND OF 12-KV. CIRCUIT, 0.035 μf. THREE 7.2-KV. POTENTIAL TRANSFORMERS. SECONDARY L/L AND L/N VOLTMETER READINGS TAKEN IN CONNECTION WITH OSCILLOGRAMS

(Approximate Primary Volts = Tabulated Volts × 60)

Refer to Fig	Line-to-line (L/L)				Line-to-neutral (L/N)				Comments	Sec. resis. bdn.	Pri. amp. N'-G
	Per cent**	1-2	2-3	3-1	1-N	2-N	3-N	Phenomenon			
8a	104	217	216*	218.7	125	125*	123	..	Normal	Vms.	†*
b	104	215.5	215	217.5	125*	126*	123*	..	Normal	Vms.	†
9a	104	216.6	215.4*	218.4	142	138*	142*	3rd	N' isolated	Vms.	..
b	104	215.2	215*	217.6	127	125*	126*	3rd	N' isolated	72 V-A.	..
4	101	210.5	210	212	195*	†*	180*	A		Vms.	†
10a	103	214	214	216	196*	†*	181*	A		Vms.	†
b*	102	212*	211	213.5	120*	125	120	A-	A didn't hold	Vms.	†
c	103	214.8*	214*	216	197	†	182	A		Vms.	†*
d	102	213.4	212	214.8	122*	122*	120*	A-	A didn't hold	72 V-A.	†
5a	101	210	209.5	212.7	331*	327.5*	333*	B		Vms.	0.57
b*	102	212	211*	213.2	340	337*	340	B		Vms.	0.58
11a	104	216	215	217.2	125*	120*	122*	B-	B (and D) didn't hold	Vms.	†
b	101	210.4	209.2	212.8*	338*	335	340*	B	1.5 cycles of D	Vms.	0.575
c*	102	212	211.5	214	197	†	182	A B	B didn't hold	Vms.	†
d*	101	210.2	209.4	212.8	336.5	332	336.5	B	Beats	Vms.	0.575*
e*	101	209.5	208.4	211.4	335	331.5	336	B		Vms.	0.575*
f*	100	208.5	207.6	211	120*	122	119	B-	307* volts N-"N"‡	288 V-A.	†

Item shown in Fig.; primary line current also shown when Fig. No. is marked thus (10b).

**Approximate—based on potential transformer rating of 208 volts L/L (= 1.73 × 120 volts L/N); values for B are about 3 per cent too low—See note in Table II.

†Value too low to read on instrument used.

‡Voltage between transformer secondary neutral N (or G) and resistor neutral "N" during B.

are shown in Fig. 11c, A existing at the start and finish and B through the center; these currents combine to form the neutral current N'-G shown in Fig. 10c.

A was always reduced to normal by adding a protective resistor burden of 72 volt-amperes (at 120 volts) per transformer; the effect of these burdens on the three L/N voltages is shown in Fig. 10d. A (and possibly B) started, existed for a few cycles and then relapsed into normal. A short time delay should be provided, therefore, for a ground relay connected across the broken delta, when the secondaries are so connected, in order to prevent incorrect operation during the starting transients. In any case, the voltage across the broken delta equals approximately 3 times the voltage N-Z, which is represented for various conditions in Fig. 2.

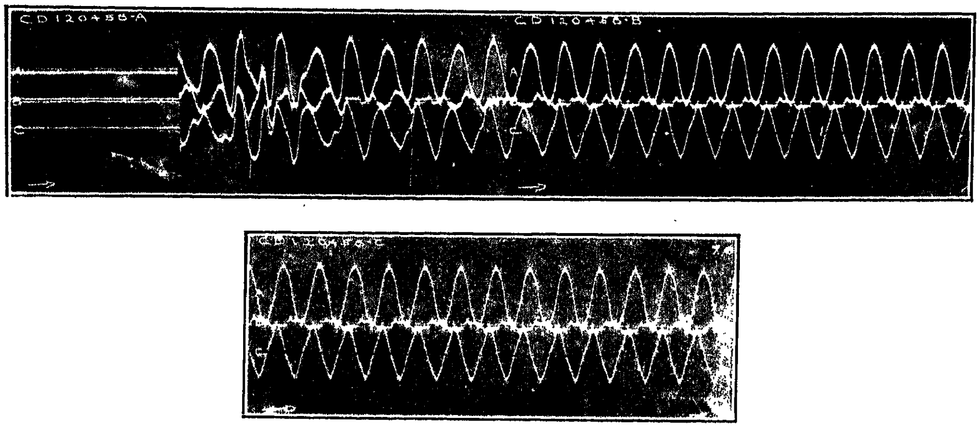
If sine-wave voltages are assumed for the readings in Tables II and V, the neutral N will be found to be located just outside the delta-voltage triangle at 94 per cent voltage as in Fig. 2b, just on the edge in most cases at 100 per cent voltage and just inside at 104 per cent voltage; in no case is the low voltage reversed in phase.

Phenomenon B. There was no mistaking the occurrence of Phenomenon B; in fact, the audible evidences of distress in the potential transformers, consisting of magnetic beats and excessive corona, first called attention to the situation, when preparing to synchronize under the conditions indicated in Fig. 1a. B is the most spectacular and at the same time the most sensitive to external conditions of any of the phenomena which held for an appreciable length of time: for example, at rated L/L voltage or higher, B failed to hold on a rainy night; also on a dry night when the bus-disconnect switches in Fig. 3 were closed, thus adding the short bus section up to the oil switch.

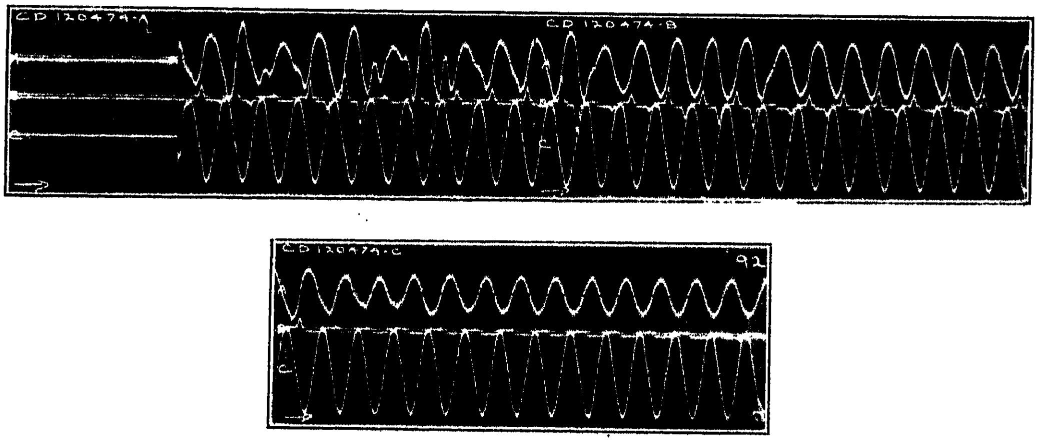
Out of 350 operations of the oil switch, 21 (about 6 per cent of total) sets of B voltage readings were obtained; however, probably three times as many started out as B and relapsed into normal, while perhaps two or three relapsed into A. It is interesting to note that heavy input-current surges to the 110-kv. power transformer bank were occasionally observed (measuring equipment not shown in Fig. 3) when the oil switch was closed; these surges apparently coincided with the start of B.

The three double-frequency L/N voltages are shown in Fig. 5a; the maximum crest value is about 615 volts (36.9 kv. primary, or 3.6 times normal crest). Voltages 2-N, 3-2 and current 2′ are shown in Fig. 5b. The relation between voltage 2-N and current 2′ is shown for a few cycles, the current peaks coinciding approximately with the zero-voltage points of alternate cycles; the maximum current crest value is about 1.3 amperes (33 times rated full-load crest). The relation between the two dents or teeth per half-cycle of voltage wave 3-2 and the peaks of current 2′ is clearly shown, although current 3′ evidently contributes in some places. The excessive exciting currents cause large unsymmetrical voltage drops in the transformer primary windings and thus distort and reduce the induced voltages, which combine in the secondary circuits to form the L/L voltages shown in the figures.

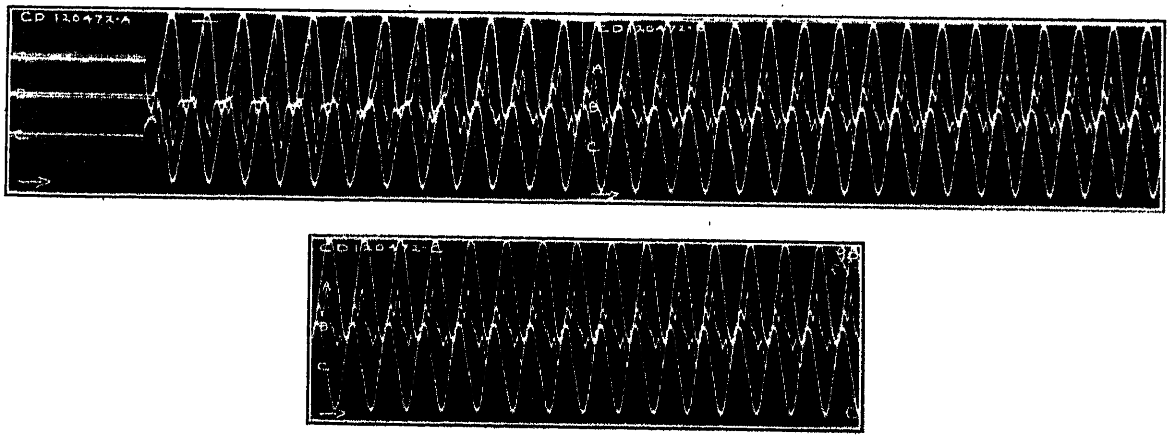
The start of the three L/N voltages is shown in Fig. 11a. The maximum crest value after stabilization is



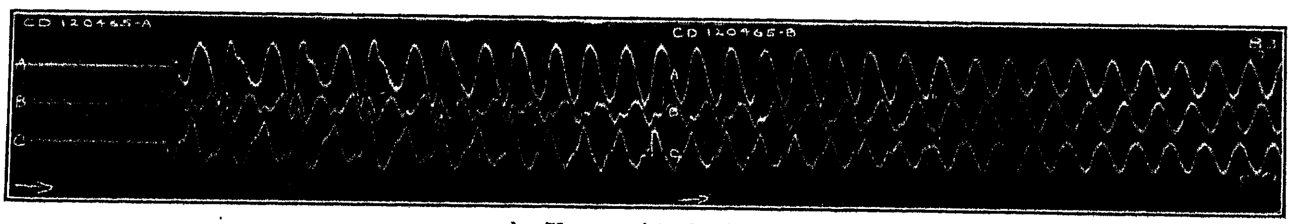
Curve A, voltage 1-N
Curve B, voltage 2-N
Curve C, voltage 3-N



b. (Also "normal")
Curve A, voltage 1-N
Curve B, current line 1′
Curve C, voltage 2-1

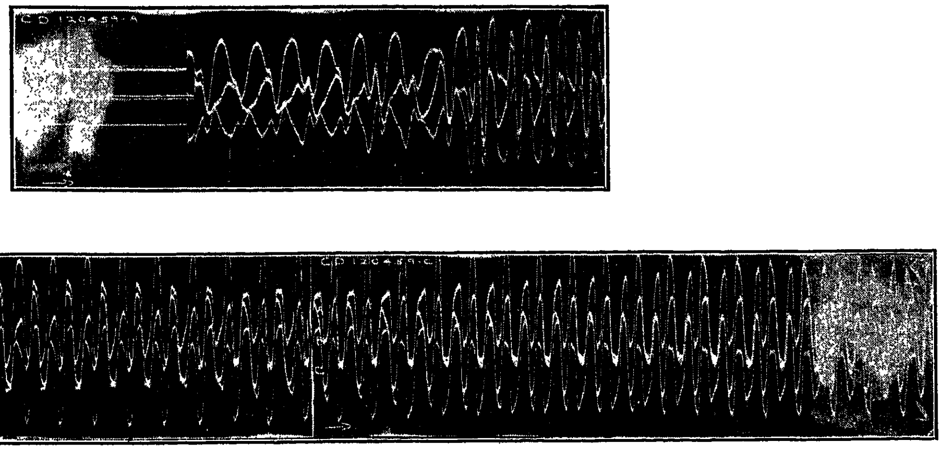


c. Curve A, voltage 3-2
Curve B, current N'-G
Curve C, voltage 2-1

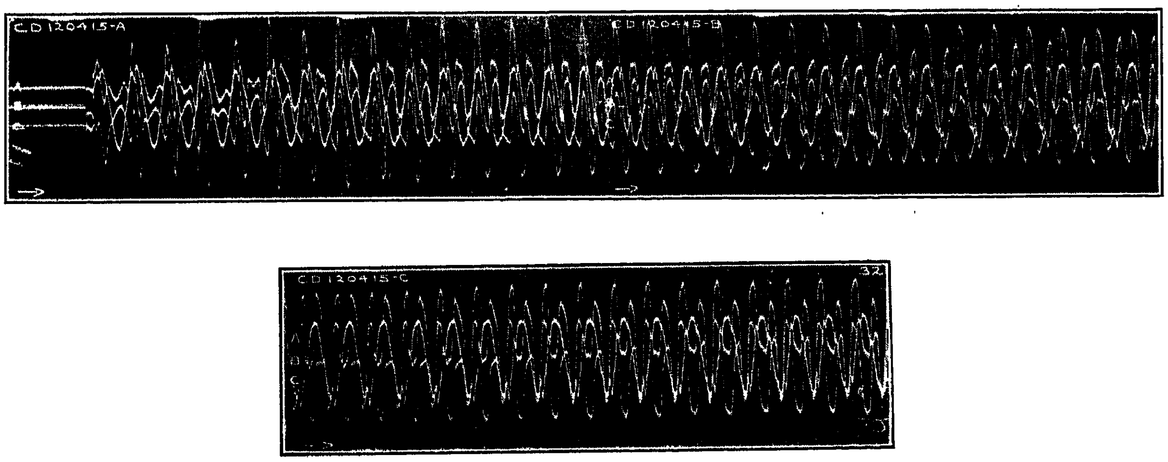


d. 72-v-a. resistor burdens (also "normal")
Curve A, voltage 1-N
Curve B, voltage 2-N
Curve C, voltage 3-N

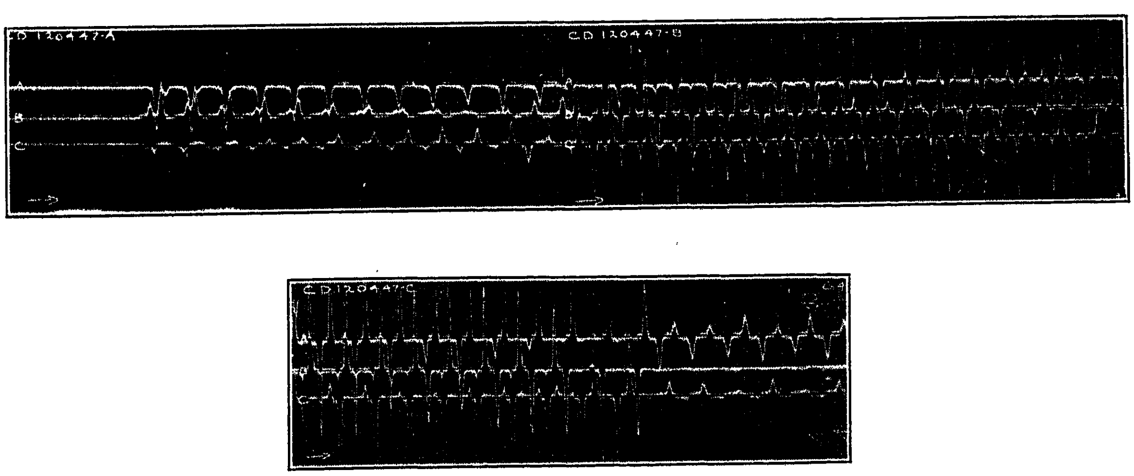
Fig. 10—7.2-Kv. Potential Transformers—Start of Phenomenon A



a. Start (also D)
Curve A, voltage 1-N
Curve B, voltage 2-N
Curve C, voltage 3-N

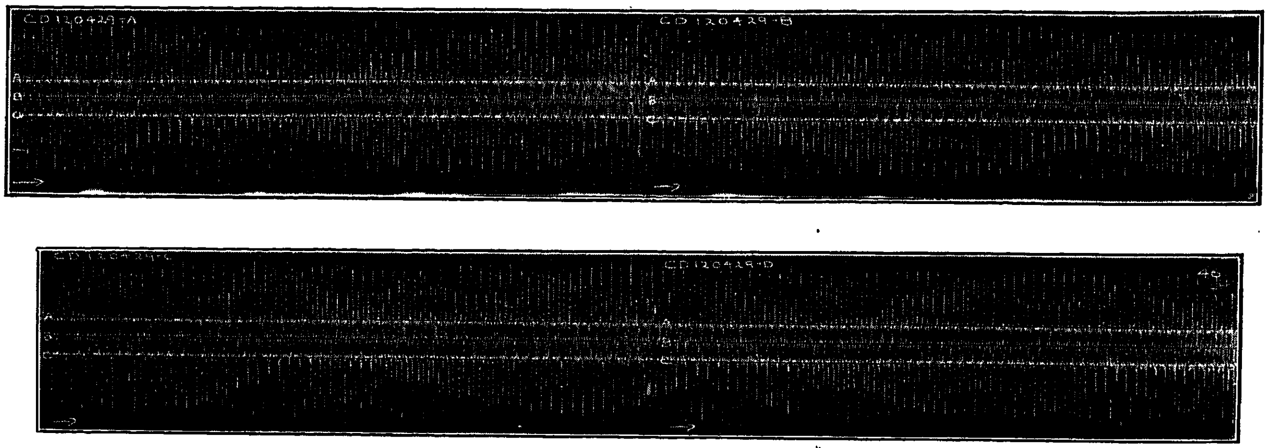


b. Start (also D)
Curve A, voltage 1-N
Curve B, voltage 1-3
Curve C, voltage 3-N

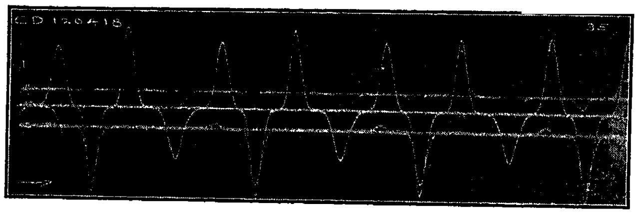


c. Start (also A)
Curve A, current line 1′
Curve B, current line 2′
Curve C, current line 3′

Fig. 11—continued next page



d. Beats
Curve A, current line 1′
Curve B, current line N'-G
Curve C, current line 3′



e. Curve A, current line 3′
Curve B, current line N'-G
Curve 3, current line 1′

f. 288-v-a. isolated-neutral resistor burdens
Curve A, current line 1′
Curve B, voltage between transformer and burden neutrals
Curve C, voltage 1-N

FIG. 11—7.2-KV. POTENTIAL TRANSFORMERS—PHENOMENON B

TABLE VI

12-KV., 60-CYCLE SYSTEM. CAPACITANCE TO GROUND OF 12-KV. CIRCUIT, 0.035 μf. POTENTIAL TRANSFORMER COMBINATIONS AND DISTRIBUTION TRANSFORMERS. SECONDARY L/L AND L/N VOLTMETER READINGS TAKEN IN CONNECTION WITH OSCILLOGRAMS

Refer to Fig.	Line-to-line (L/L)				Line-to-neutral (L/N)				Comments	Trans-former ratio	Pri amp. N'-G
	Per cent**	1-2	2-3	3-1	1-N	2-N	3-N	Phenom-enon			
Six 7.2-kv., 0.2-kv-a. potential transformers											
12*	100	209*	208.2	211	125*	120	115	*A B D*-	Normal not shown	60:1	†
Three 7.2-kv. and three 13.2-kv. potential transformers											
13	103/56	106*	108	107	62.5*	62.5*	62	*A B D*-	Vms. changed	120:1	†
	103/56	108	108	108	91.5	93	†	*A*	For *A* in Fig. 13	120:1	†
Three 6.9-kv., 1.5-kv-a. distribution transformers											
14a	107	212*	211	213.5	125*	120*	124	*A*-	Normal not shown	60:1	†
b*	104	207*	206	209.5	123*	114	122	*A B D*-	Normal not shown	60:1	†
	106	210	209.5	212.5	284	282	287	*B*	For *B* in Fig. 14b	60:1	0.5
5.96-kv. tap on 6.9-kv. distribution transformers											
15	122	242.8*	241.5	244.5	140*	140*	142	*A B D*-	Normal not shown	51.8:1	†
	119	‡	‡	236	485	480	483	*D*-	For *D* in Fig.15	51.8:1	‡
	120	238	238	240	233	†	238	*A*	For *A* in Fig.15	51.8:1	†
Two 7.2-kv. potential transformers connected L/N											
16*	102	212*			135*	125		*A B D*-		60:1	†
	102	213			173	175		*A*	For *A* in Fig.16	60:1	†
	102	212.5			220	219		*B*	For *B* in Fig.16	60:1	0.3

Item shown in Fig.; primary line current also shown when Fig. No. is marked thus (12).
**Approximate—based on 1.73 × L/N voltage rating—values for *B* (and probably for *D*) are too low—See note in Table II.
†Value too low to read on instrument used.
‡Reading not obtained.

about 615 volts, same as in Fig. 5a, but the maximum crest before stabilization is about 655 volts; the latter is attributed to the momentary existence of Phenomenon *D*. The slow variations in alternate successive positive (or negative) crest values are at the rate of approximately 90 per min. and are accompanied by

changes in wave form. Somewhat similar remarks apply to Fig. 11b, which shows voltages 1-N, 3-N, and 1-3. The maximum D crest is about 675 volts (40.5 kv. primary, or 4 times normal crest); variations are noticeable in the wave shape of the L/L voltage, which also serves as a timing wave.

The start of the three primary line currents is shown in Fig. 11c. This operation started and finished as A,

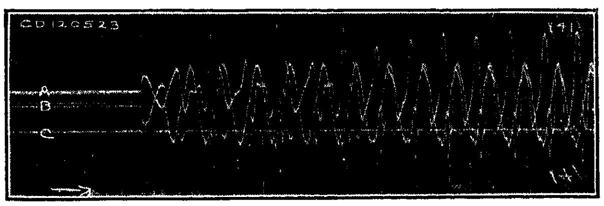


Fig. 12—Six 7.2-Kv. Potential Transformers (Two Y-Banks)—Start of Phenomena A, B, and D

Curve A, voltage 1-N
Curve B, voltage 2-1
Curve C, current line 1′

but B held long enough to show the relations between the three currents, which combine to form the neutral current N'-G shown in Figs. 11d and e. The peaks in the different lines are not in phase, except (approximately) when one peak is small; this means that the crest values of the neutral current N'-G do not greatly exceed those of the line currents.

Fig. 11d shows particularly the variations in the alternate successive positive (or negative) crest values of currents 1′, 3′, and N'-G, which occur at the rate of approximately 260 per min. for the double-frequency neutral current and 85 per min. for the line currents. The approximate maximum crest values are 1.75 amperes for current N'-G and 1.6 amperes for currents 1′ or 3′. The same currents are shown more spread out in Fig. 11e; the differences between the adjacent negative crest values of the neutral current are quite pronounced.

Fig. 11f shows voltage 1-N and current 1′ with an isolated-neutral burden equivalent to 288 volt-amperes per transformer. The voltage between the transformer neutral N and the burden neutral "N" is also shown; its wave shape is somewhat more symmetrical than that of voltage 1-N. The small current drawn by the oscillograph and volt-meter prevented B from holding; when these devices were not connected B held indefinitely.

B failed to hold with one group of transformers, because one transformer arced over. When the defective transformer was replaced, this difficulty disappeared. This transformer was later given a standard high-potential test at 25 kv. and showed no evidences of distress. The arc-overs might have been due to momentary cycles of D.

B was usually reduced to normal by changing the L/N oscillograph resistor settings to 1,000 ohms (14.4 volt-amperes) from 4,000 ohms (3.6 volt-amperes). The increase in actual L/N burden thus amounted to about 11 volt-amperes at 120 volts; much greater L/L or equivalent L/N burdens had little effect in this respect, as is evident from the description of Fig. 11f.

(b) Miscellaneous Transformer Combinations

Phenomena A, B, and D

This section includes results on five different transformer combinations. Voltmeter and ammeter readings taken in connection with the figures described are given in Table VI; supplementary sets of readings, corresponding to the various phenomena shown in the figures but not taken at the same time, are included when available.

Fig. 12 shows the start of voltages 1-N, 2-1 and current 1′ for two banks of 7.2-kv. potential transformers; the primaries but not the secondaries were connected in multiple. A trace of Phenomenon A and perhaps three separate cycles of D are shown at the start and

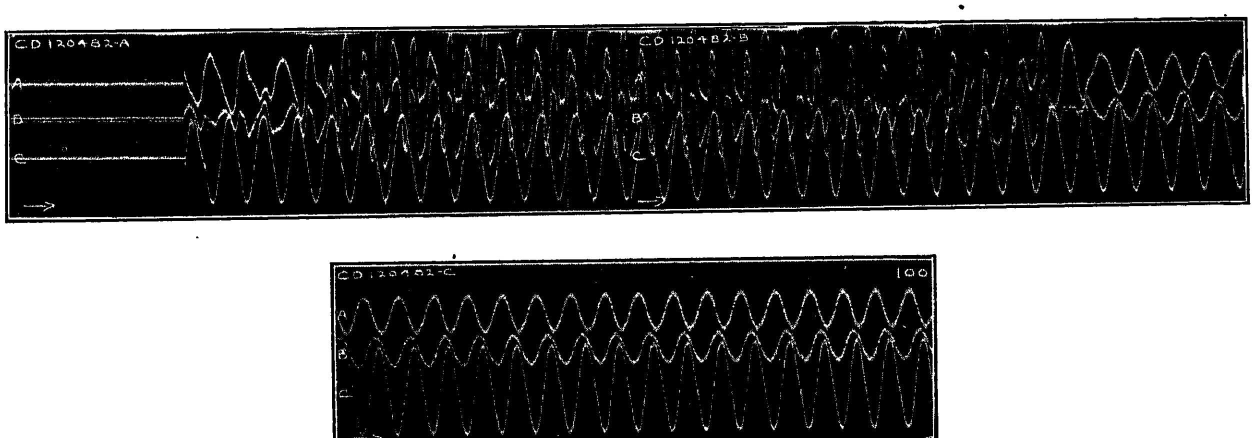


Fig. 13—Three 7.2-Kv. and Three 13.2-Kv. Potential Transformers (Two Y-Banks)—Start of Phenomena A, B, D and "Normal"

Curve A, voltage 1-N
Curve B, voltage 2-N
Curve C, voltage 2-1

several cycles of B are shown subsequently. The maximum voltage and current crest values for D are somewhat higher than for B; the existence of a large triple-frequency current to ground during D is indicated by the three teeth per half cycle of the L/L voltage, whereas there are only two for the double-frequency current to ground during B. The approximate L/N voltage for B was 290 volts; this value was obtained during the brief intervals when B started and held temporarily in 17 out of 28 operations of the oil switch; the other 11 operations apparently started out as, and the 17 relapsed into, normal.

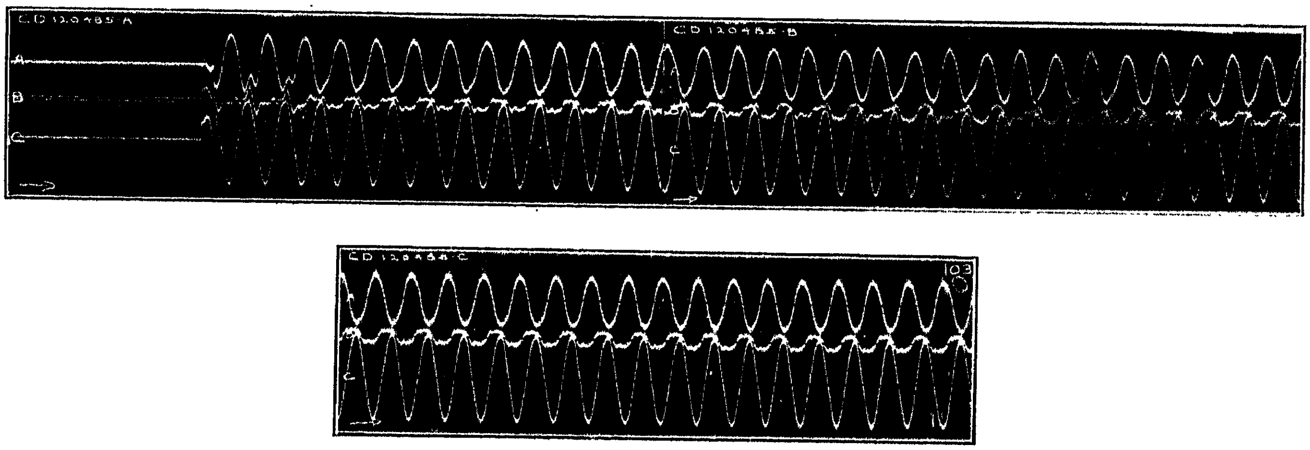
TABLE VII

12-KV., 60-CYCLE SYSTEM. CAPACITANCE TO GROUND OF 12-KV. CIRCUIT, 0.845 μf. THREE 7.2-KV. POTENTIAL TRANSFORMERS. SECONDARY L/L AND L/N VOLTMETER READINGS TAKEN IN CONNECTION WITH OSCILLOGRAMS

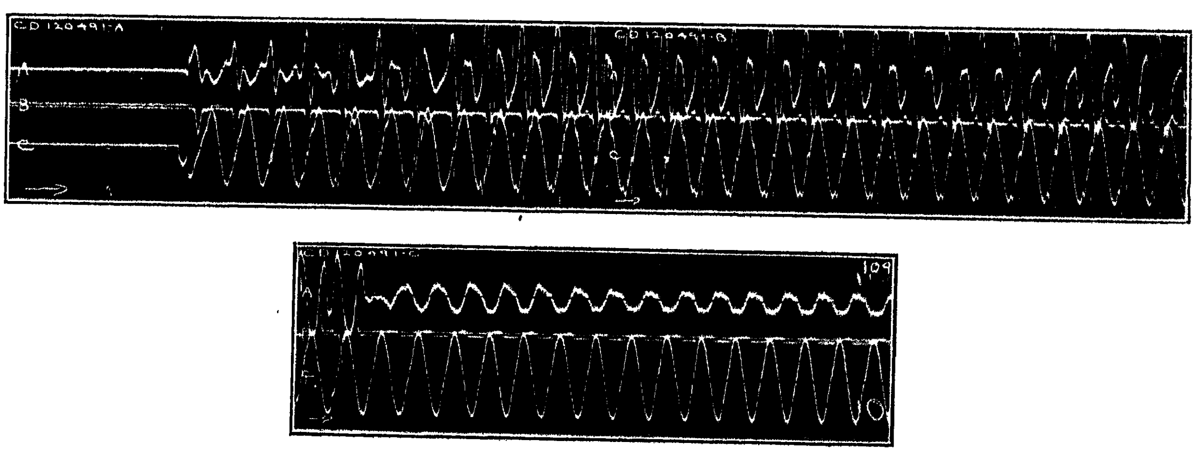
(Approximate Primary Volts = Tabulated Volts × 60)

Refer to Fig.	Line-to-line (L/L)				Line-to-neutral (L/N)				Comments	Pri. amp. N'-G
	Per cent†	1-2	2-3	3-1	1-N	2-N	3-N	Phenomenon		
6*	96	197.5	199	200*	147	148	149*	C		0.88
17a	95	196	197.4	199	148*	148*	149*	C		0.89
b*	96	198	199.2	201*	149	149	150*	C		0.88
c*	96	198	198.8	200.5	147	148	140	C	Beats	0.88
d	96	197.5	198.8*	200.5*	146	148	149	C		0.87*
	100	207	208	209.2	120	119	122	..	Normal	‡

Item shown in Fig.; primary line current also shown when Fig. No. is marked thus (6).
†Approximate—based on potential transformer rating of 208 volts L/L (= 1.73 × 120 volts L/N); values for C are about 4 per cent too low.
‡Value too low to read on 5-ampere ammeter.



a. A
Curve A, voltage 1-N
Curve B, voltage 2-N
Curve C, voltage 2-1



b. A, B and D
Curve A, voltage 1-N
Curve B, current line 1′
Curve C, voltage 2-1

FIG. 14—6.9-KV., 1.5-KV-A. DISTRIBUTION TRANSFORMERS—START OF PHENOMENA

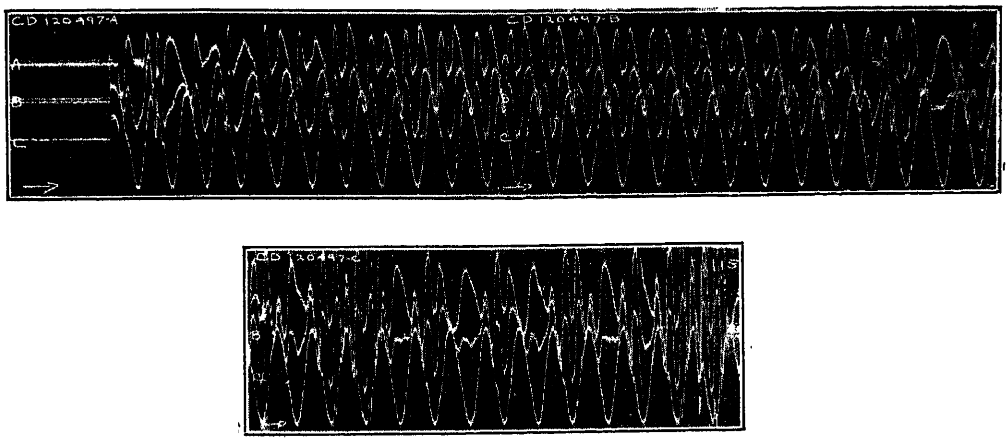


FIG. 15—5.96-KV. TAP ON 6.9-KV. DISTRIBUTION TRANSFORMERS—START OF PHENOMENA A, B AND D

Curve A, voltage 1-N
Curve B, voltage 2-N
Curve C, voltage 2-1

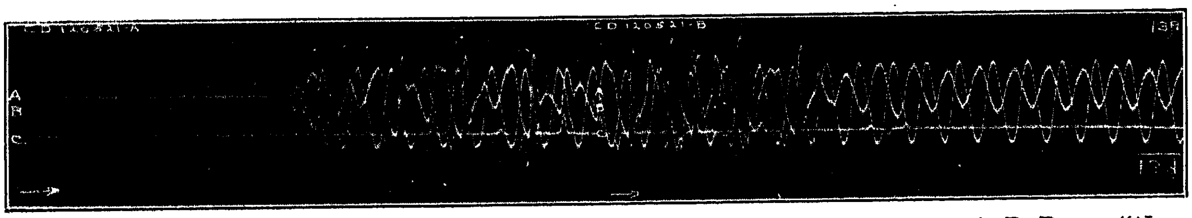


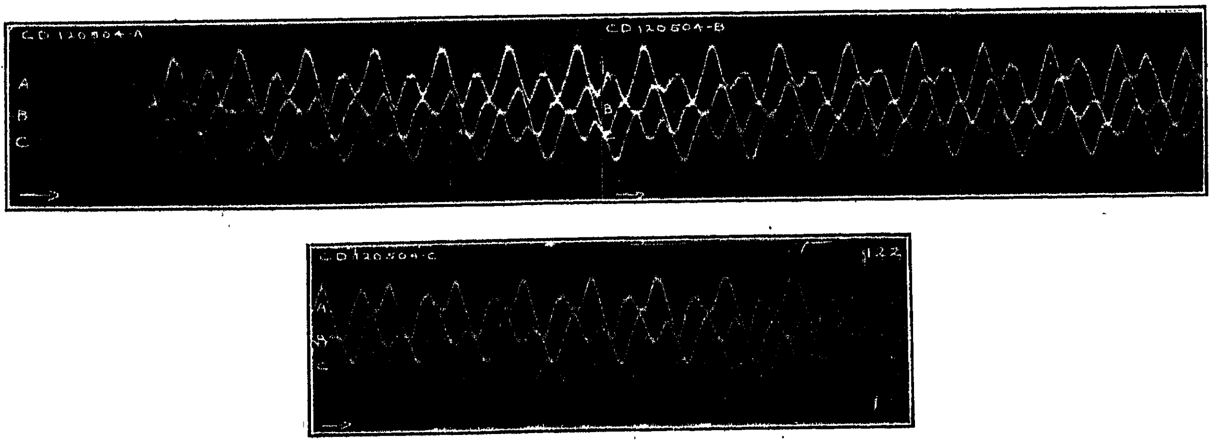
FIG. 16—TWO 7.2-KV. POTENTIAL TRANSFORMERS (CONNECTED L/N)—START OF PHENOMENA A, B, D AND "NORMAL"

Curve A, voltage 1-N
Curve B, voltage 2-1
Curve C, current line 1′

The start of voltages 1-N, 2-N and 2-1 is shown in Fig. 13 for one bank of 7.2-kv. and one bank of 13.2-kv. potential transformers in multiple; the voltage readings and oscillograms were taken on the 13.2-kv. transformer secondaries. Traces of A and D are shown at the start and several cycles of B and normal are shown subsequently. Practically no distortion appears in the L/L voltage, indicating that the phenomena were generated solely by the 7.2-kv. bank.

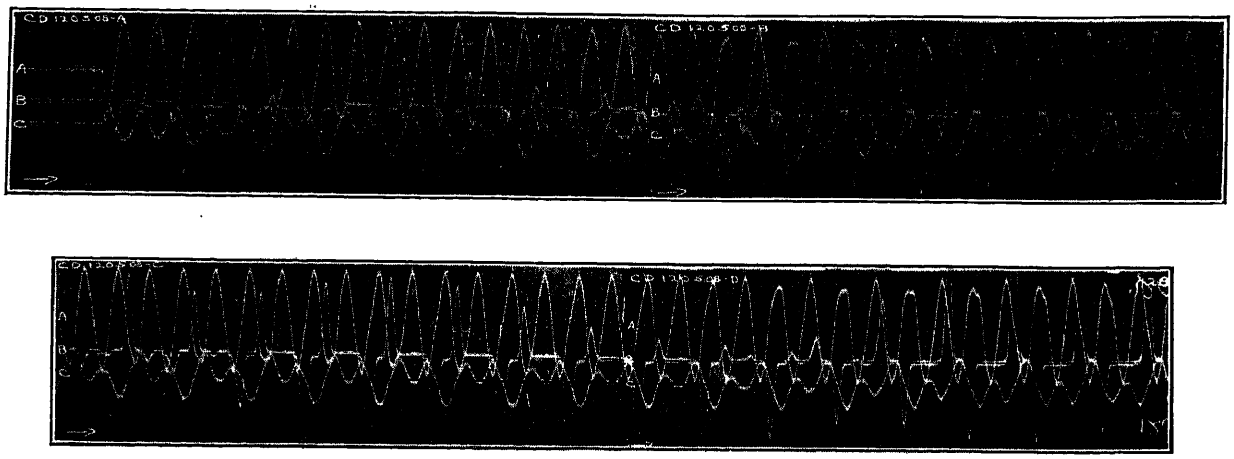
Fig. 14a shows the start of voltages 1-N, 2-N and 2-1 in A for one bank of 6.9-kv., 1.5 kv-a. distribution transformers; voltage 2-N is low. Fig. 14b shows the start of voltages 1-N, 2-1 and current 1′. Perhaps three separate cycles of D are shown; the crests of the accompanying currents are higher than those for B (see remarks for Fig. 12). A is shown also, with voltage 1-N low.

Fig. 15 shows the start of voltages 1-N, 2-N and 2-1 for the 5.96-kv. tap on the 6.9-kv. distribution transformers. Traces of A and several cycles of B are

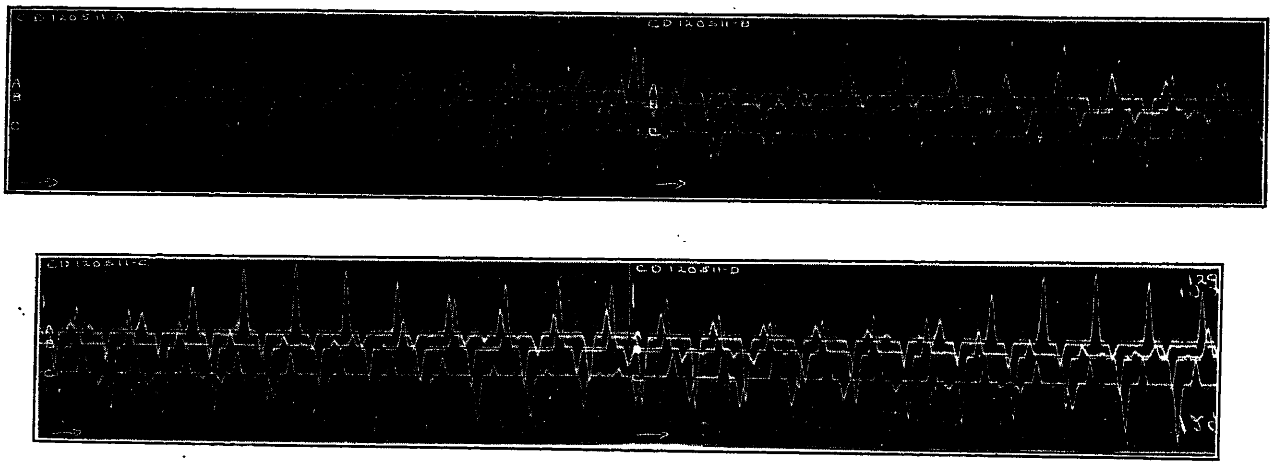


a. Start
Curve A, voltage 1-N
Curve B, voltage 2-N
Curve C, voltage 3-N

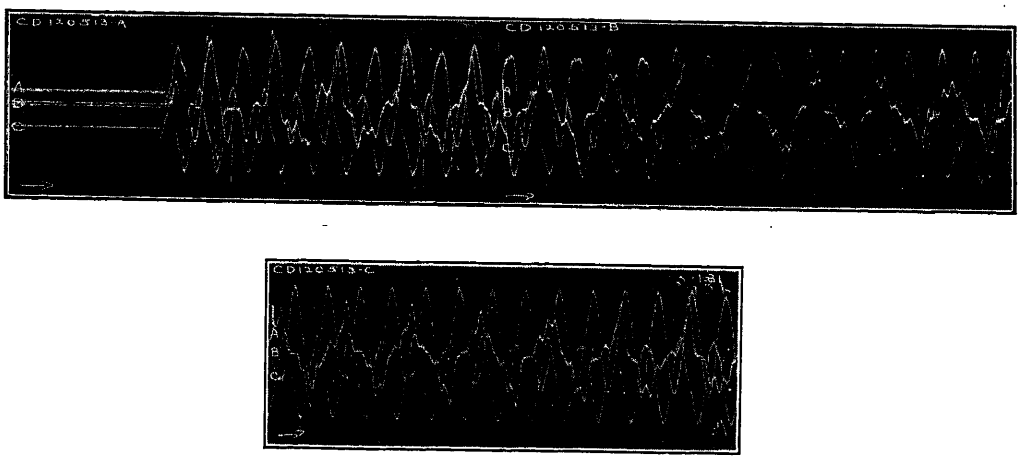
Fig. 17—continued next page



b. **Start**
Curve A, voltage 1-3
Curve B, current line 3′
Curve C, voltage 3-N



c. **Beats**
Curve A, current line 1′
Current B, current line 2′
Curve C, current line 3′



d. **Start**
Curve A, voltage 1-3
Curve B, current N'-G
Current 3, voltage 3-2

Fig. 17—7.2-Kv. Potential Transformers—Phenomenon C

shown. Two trains of several successive cycles each of D are shown; in each case, D terminated in an arc-over. The maximum crest value shown is about 650 volts (33.7 kv. primary, or 4 times normal crest). This is the only connection for which D held for more than about one cycle, thus making voltmeter readings possible; however, D did not hold long enough even in this case to obtain a complete set of readings. It is evident, therefore, that D is much less likely than B to sustain itself.

The start of voltages 1-N, 2-1 and current 1′ is shown in Fig. 16 for two 7.2-kv. potential transformers connected L/N; the third transformer was disconnected by removing its fuse. Secondary burdens 3-2 and 1-3 were disconnected to prevent partial excitation of the secondary from the other two transformers. Traces of A and possibly D and a few cycles of B and normal are shown. The maximum crest values for the B voltage and current are about 510 volts and 1.2 amperes, respectively. Evidently the phenomena are not suppressed by omitting one transformer.

TABLE VIII
CAPACITANCE-TO-GROUND TEST RESULTS

Voltmeter Reading	12-kv. Circuit: Ammeter Reading	Calculated: Volts	Calculated: Impedance ohms	Calculated: Capacitance μf.	Description (see Fig. 3)
100	3.975	12,000	3020	0.880	Complete circuit
100	3.815	12,000	3145	0.845	Generator only
				0.035	Bus and transformers only

(2) Supplied from 25,000-Kv-a. Generator-Capacitance to Ground of 12-Kv. Circuit, 0.845 μf.

THREE 7.2-KV. POTENTIAL TRANSFORMERS

Phenomenon C. The occurrence of Phenomenon C was evidenced audibly only by magnetic beats, since the L/N voltages were too low to cause corona. Voltmeter and ammeter readings taken in connection with the figures described are given in Table VII.

Fig. 6 shows voltages 3-N, 1-3 and current 3′; the relation between voltage 3-N and current 3′ is shown for a few cycles, the current peaks coinciding approximately with the zero-voltage points of alternate cycles; the maximum current crest value is about 1.75 amperes (45 times rated full-load crest). Fig. 17a shows the start of the three L/N voltages; slow variations in wave shape occur at the rate of about 53 per min. Fig. 17b shows the start of voltages 3-N, 1-3 and current 3′. The distortion of the L/L voltage wave caused by the excessive exciting currents is shown more clearly in Fig. 17b than in Fig. 6.

Fig. 17c shows the three line currents, which combine to form the neutral current N'-G shown in Fig. 17d. Slow variations in successive positive (or negative) crests occur at the rate of about 120 per min.; the maximum crest value is about 2.1 amperes (54 times rated full-load crest). Fig. 17d shows the start of voltages 1-3, 3-2 and current N'-G. Variations in the wave shape of the latter are noticeable; the maximum crest value at the start is about 2.9 amperes and after stabilization, 2.3 amperes.

At rated voltage, C was reduced to normal by adding a protective resistor burden of 72 volt-amperes (at 120 volts) per transformer. A larger burden was necessary at higher voltages, but it was not anticipated that such voltages would be encountered under normal operating conditions.

(II) DETERMINATION OF CAPACITANCE TO GROUND

The approximate test results outlined here were obtained by the volt-ampere method as described under "Methods of Test." Representative instrument readings taken are given in Table VIII, together with the calculated impedance and capacitance to ground of the 12-kv. circuit. Owing to the fact that the capacitance to ground of the 12-kv. bus and transformers was only a small fraction of either of the two calculated values from which it was determined, a check test was made by a more direct method. The result obtained was about 5 per cent greater than 0.035 μf.; part of this was due to the fact that no allowance was made for the voltage rise in the potential transformer. This close agreement between the two sets of results is very satisfactory under the circumstances.

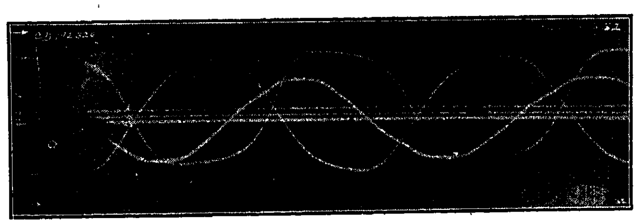


FIG. 18—SIX 63.5-KV. POTENTIAL TRANSFORMERS (ONE Y-Y BANK; ONE Y-BROKEN-DELTA BANK)—PHENOMENON A

Curve A, voltage across broken delta
Curve B, voltage 3-N
Curve C, voltage 1-2

It was not possible to determine the capacitance to ground of each of the three phases under the different conditions. However, there is no reason to believe that it should differ appreciably from one-third of the proper total value obtained from test.

110-Kv., 25-Cycle System

OPERATION OF 63.5-KV. POTENTIAL TRANSFORMERS

Phenomenon A. The occurrence of Phenomenon A at rated L/L voltage or higher was evidenced audibly by increased corona, due to the comparatively high voltage (110 kv. or more) to ground on two of the lines. The voltage waves obtained for A (and B) and the normal condition were of the same general shapes as those on the 12-kv. system, so only two figures are

included, both of which were obtained when two banks of potential transformers (one Y-Y; one Y-broken delta) were connected in multiple; this represents the usual operating condition. Voltmeter readings for these figures are given in Table IX; for *A*, the neutral is displaced from its normal position by approximately one-third the reading of the voltmeter connected across the secondary of the Y-broken delta bank.

Out of 27 operations of the oil switch at rated voltage, 15 (about 56 per cent of total) sets of normal voltage readings and 12 (about 44 per cent of total) sets of *A* voltage readings were obtained; of the latter, voltages 1-*N*, 2-*N* and 3-*N* were too low to read on their respective voltmeters in the ratio of 50 to 33 to 17.

The start of the three *L/N* voltages is shown in Fig. 7; initial oscillations occur at the rate of approximately 4,200 cycles per sec. About one-half cycle of Phenomenon *B* and two cycles (after stabilization) of *A* are shown.

TABLE IX

110-KV, 25-CYCLE SYSTEM. SIX 63.5-KV. POTENTIAL TRANSFORMERS. CONNECTIONS: ONE BANK, Y-Y; OTHER BANK Y-BROKEN DELTA. SECONDARY VOLTMETER READINGS TAKEN IN CONNECTION WITH OSCILLOGRAMS

(Approximate Primary Volts = Tabulated Volts × 1000)

Refer to Fig.	Line-to-line (L/L)				Line-to-neutral (L/N)				Comments	Broken-delta vm.
	Per cent†	1-2	2-3	3-1	1-*N*	2-*N*	3-*N*	Phenomenon		
7	110	121	121.5	120.3	13*‡	114.5*	121*	*A*	Part cycle of *B*	196
18	76	84.5*	84	82.2	44.5	108.2	124.7*	*A*	Volts reduced after taking Fig. 7	258*
	110	122	123	121.8	69.9	71.1	70	..	Normal 110%	4.1
	78	86.1	86.7	85.4	49.8	50	49.5	..	Normal 76%	1.8

*Item shown in Fig.

†Approximate—based on potential transformer rating of 110 volts *L/L* (= 1.73 × 63.5 volts *L/N*).

‡Estimated value.

Fig. 18 shows voltages 3-*N* and 1-2 on the Y-Y bank and the broken-delta voltage on the bank so connected. This extreme example of *A*, in which the greatest *L/N* voltage is 50 per cent greater than the *L/L* voltage and in which the neutral has been displaced by the approximate amount of the *L/L* voltage (one-third of 258 volts) from its normal position, could be obtained only by reducing the voltage after once establishing *A*.

The occurrence of *A* (and *B*) was prevented for two banks in multiple at all voltages tried by adding protective resistor burdens of 600 volt-amperes (at 63.5 volts) per transformer. The single protective burden connected across the broken delta of one bank, found to be equivalent to the six 600-volt-ampere *L/N* burdens (about 6.7 ohms each) or, preferably, to the three 1,200 volt-ampere *L/N* burdens (about 3.4 ohms each) in terms of one bank, amounted to approximately 10 ohms.

It was not possible to obtain *A* at rated voltage with only one bank of potential transformers connected; however, *A* did occur frequently at 110 per cent of rated voltage. Voltmeter readings are given in Table III.

Protective resistor burdens of 900 volt-amperes per transformer were necessary to prevent the occurrence of *A* at 110 per cent of rated voltage. The single protective burden for the Y- broken-delta bank, found to be equivalent to the three 900 volt-ampere *L/N* burdens (about 4.5 ohms each) for the Y-Y bank, amounted to approximately 13.5 ohms.

It is evident that the total resistance of the necessary protective burden is independent of its connection; for example, substantially the same protective efficiency will be obtained with 15 ohms connected across a broken delta as with three 5-ohm burdens connected Y, for the corresponding secondary connections.

If sine-wave voltages are assumed for the readings in Tables III and IX, the neutral *N* will be found to be located outside of the delta-voltage triangle in all cases, as in Fig. 2b. For two banks in multiple, *N* is near the edge at 110 per cent voltage, considerably outside at 100 per cent and far outside the triangle at 76 per cent voltage. For one bank only, *N* is considerably outside the triangle at 110 per cent voltage; in this, as in the two previous cases, the low voltage can be said to be partly reversed in phase.

Discussion

For discussion of this paper see page 342.

Physical Nature of Neutral Instability

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and

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Associate, A. I. E. E.

Synopsis.—Experience has established the fact that the neutral of a three-phase system may become subject to certain strange phenomena of instability under apparently normal conditions. The disturbances are of two distinct classes: (1) persistent shift or inversion of the neutral, resulting in unequal leg voltages; and, (2) persistent oscillation of the neutral (with equal effective voltage in all three legs) at approximately one-half, double, or triple frequency. While in the ultimate analysis saturation is at the basis of the phenomena, a more definite explanation is given as follows:

1. Neutral shift or inversion is a fundamental frequency phenomenon, and is due to the fact that the volt-ampere curve of the combination of an iron core reactor (transformer magnetizing current) in shunt with a suitable capacitor has one zone which is lagging and one which is leading. In a Y-Y bank of transformers, with suitable balanced line capacitances to neutral following a switching disturbance, one leg may act leading, the others lagging, and thus invert the neutral.

2. Oscillations of the neutral tend to take place at its natural frequency, but since, due to inevitable losses, not all oscillations can persist, in course of the starting transient the oscillation is resolved to the nearest lower frequency which is able to draw energy from the circuit by approximating harmonic relationship to it. The even harmonics are accounted for by the persistence of residual in the core, whether left from previous excitation or brought about by the direct current component of starting transient.

In single-phase circuits, the half-frequency oscillations of the neutral are exactly half frequency, but in three-phase circuits it may deviate from this somewhat, producing a continued phase-shift between the neutral potential and the impressed frequency, and resulting in beats.

It is commonly recognized that in a core subject to saturation energy can be put in at fundamental frequency and drawn out at a higher harmonic. This principle is here amplified and made reversible by postulating that energy may flow not only from fundamental to its harmonics but also from these harmonics to fundamental, if a suitable source of harmonic energy is connected to the circuit. This principle is then generalized whereby energy may flow not only from a higher harmonic to fundamental, but also from fundamental to an oscillation at subnormal or fractional frequency, the fundamental acting as a higher harmonic of the oscillation at subnormal frequency.

Laboratory tests are described (a) reproducing some of the disturbances observed in the field, and (b) supporting the theories outlined above.

Preventative measures and laboratory tests with them are also discussed.

* * * * *

INTRODUCTION

FROM time to time the attention of the Institute has been drawn to some peculiar troubles accompanying the operation of Y-Y connected transformers with their neutral grounded on an otherwise isolated system.[2] Such a scheme of operation is objectionable for other reasons besides the peculiar phenomena observed, and power transformers are not operated in this fashion nowadays, unless equipped with tertiary delta windings. The peculiar phenomena referred to above were, therefore, of only theoretical interest for many, until it was learned that such a scheme of operation is being used in a number of potential transformer installations, constituting a possible hazard to the system and connected apparatus. In view of the importance of the problem, and the obscurity of the phenomena, a combined theoretical and laboratory study was recently undertaken by the authors to elucidate the physical nature of the phenomena. The conclusions arrived at here are in some respects different from those of earlier investigators reported to the Institute, although not inconsistent with the works of Heegner[3] and Lampert[4] in Germany. The studies of these latter authors, however, have a bearing on only one group of the phenomena here discussed. Although the theories here advanced need not be considered complete in all detail, they are believed to interpret correctly the physics of these disturbances.

The phenomena under discussion are found only in circuits with capacitance and saturation, and therefore, it is proposed to build up the present discussion starting with an analysis of the characteristics of iron-core reactors in combination with capacitors.

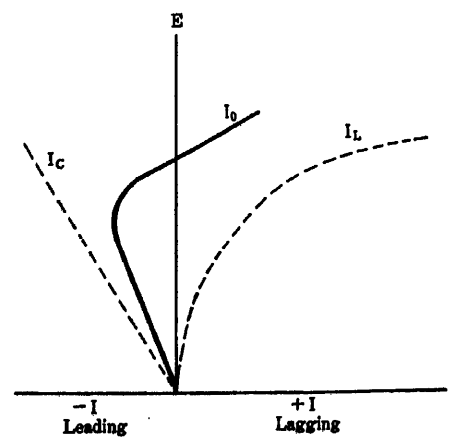


FIG. 1—VOLT-AMPERE CURVE OF AN IRON-CORE REACTOR AND A CAPACITOR IN PARALLEL

I_L, curve for reactor; I_C, curve for capacitor; I_0, resultant of the two in parallel

IRON-CORE REACTOR SHUNTED BY A CAPACITOR

In Fig. 1, the dotted curve I_L is the volt-ampere characteristic of the saturating inductance, such as the magnetizing current of a transformer, and dotted curve I_C is that of the shunt capacitance. The resultant

1. Both of General Electric Company, Pittsfield, Mass.
2. For references see Bibliography.

Presented at the Southern District Meeting No. 4, of the A. I. E. E., Louisville, Kentucky, November 19-22, 1930.

characteristic curve of the combination is shown by the heavy curve I_o. It is realized that the exciting current of a transformer is much more complicated than that of a capacitor. While the latter may be considered as yielding a pure leading current, the former will always contain a lagging component, a power component and harmonics. As the lagging component is frequently 80-90 per cent of the total exciting current, it is important to know its behavior in the network, and Fig. 1 is drawn

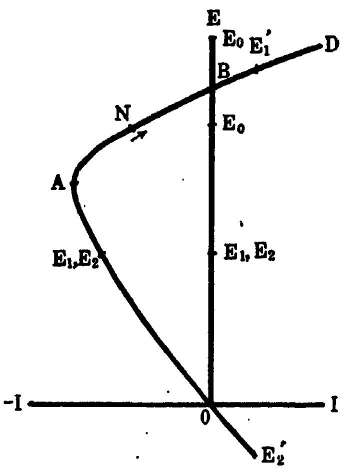


Fig. 2—Details of I_o from Fig. 1

for the fundamental frequency reactive components of the currents. The effect of losses and harmonics will be discussed later.

A magnified curve of I_o is given in Fig. 2, and three zones are marked on it for detailed analysis and comparison.

Zone O-A. Fig. 2. In this zone I_o is leading, and the combination behaves like a capacitive reactance. As the graph is substantially straight, the circuit parameter; that is, the equivalent capacitive reactance of the combination, is constant; and the behavior of the circuit is stable, like any linear impedance.

Zone A-B. Fig. 2. This zone covers the same current values as in *O-A* but at a higher voltage, so that the function *O-A-B* is double valued. Furthermore, in the zone *A-B*, with increasing voltage the current decreases. In terms of impedance, the gross apparent reactance of the combination for the main current is still leading or capacitive, but its incremental reactance; that is, the reactance for superposed smaller currents, is lagging or inductive.

X, considered as $\dfrac{E}{I}$ is negative, leading, capacitive; but,

X, considered as $\dfrac{\Delta E}{\Delta I}$ is positive, lagging, inductive.

Now such a characteristic is a source of instability *under suitable conditions*, somewhat analogous to the case of an arc of which the incremental resistance is opposite to its gross resistance and leads to instability under certain conditions. If, in a network, such a combination operating at the point N is in equilibrium, in the sense that the terminal conditions will be satisfied thereby, such an equilibrium may be unstable when disturbed, the point N moving either up into zone *B-D* or down into zone *O-A* to find a point of stable equilibrium, or it may fail to reach equilibrium and the point N may remain in a state of persistent oscillation. Corresponding to these two cases to be discussed later in detail, namely, where an abnormal condition of equilibrium is established, or, where the point N oscillates indefinitely, we have the two categories of troubles experienced in the Y-Y operation of potential transformers, namely, inversion or shifting of the neutral and the oscillation of the neutral.

Zone B-D. Fig. 2. In this zone, the current is lagging, and increases with the voltage (even though not in direct ratio); so that both the gross and the incremental reactance of the combination are inductive, and the behavior of the combination is substantially that of a plain saturating inductive reactance. An equilibrium point in this zone tends to be stable.

We may now proceed to build up the characteristics of such combinations in networks, with particular reference to the inversion of neutral and the oscillation of neutral.

Inversion of Neutral

(*a*) *Inversion in a Single-Phase Circuit.* Referring to Fig. 3A, let branches 1 and 2 be duplicates. A point

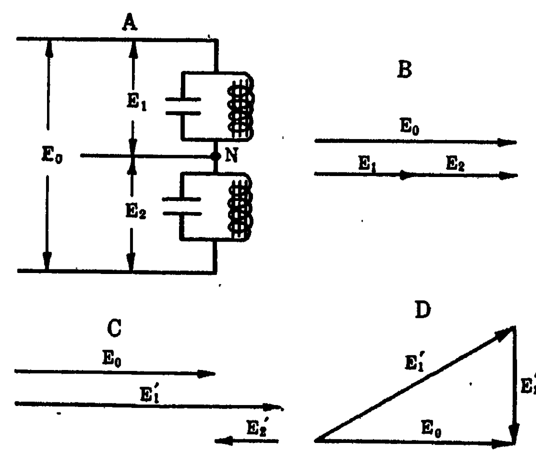


Fig. 3

A. Single-Phase Circuit with Unstable Neutral
B. Vector Diagram for Normal Condition of Neutral
C. Vector Diagram for Inverted Neutral
D. Vector Diagram for Neutral Inversion with a Prominent Quadrature Component

of equilibrium for N is obviously half way between the potentials of the terminals, as shown in Fig. 2, and also by the vector diagram of Fig. 3B:

$$E_1 = E_2 = E_0/2,$$

where E_0 is the line voltage, and E_1 and E_2 are the branch voltages. If the branch voltages E_1 and E_2 are

within the zone O-A (as shown in Fig. 2), the potential of N will be normal and stable, once so established. In Fig. 3B the line current will be leading, both branches acting capacitively. Assume, however, that when the line switch is closed, the starting transient unbalances the voltages and carries one of the branch voltages, say E_1, into zone A-D. A new and abnormal condition of equilibrium may now become established as follows:

Considering the characteristic curve, Fig. 2, it is seen that not only

$$E_1 + E_2 = E_0,$$

but also,

$$E_1' + E_2' = E_0.$$

In the latter case, E_2' is negative, E_1' is greater than the line voltage (see also the vector diagram of Fig. 3C), and the neutral potential is outside of the line voltage. Obviously, one leg or branch of the circuit is acting inductively, the other capacitively.

With a different line voltage, say E_0'', (Fig. 2), a still different type of abnormal equilibrium may take place with the leg or branch voltages assuming the values E_1'' and E_2'' respectively, in which case then, both branches are operating capacitively, one overexcited, the other underexcited.

A still different position of the neutral may correspond to one leg operating in the zone A-B, the other in the zone B-D, both legs overexcited. Such a case was observed in single-phase tests.

Effect of Losses and Harmonics. The effective resistance of each branch will obviously give a voltage drop in quadrature with the reactive drop, and since the ratio of resistance to reactance may not be the same in both branches, E_1' and E_2' need not be parallel to each other, but may be out of phase, as shown in Fig. 3D. The losses may thus modify the position of the neutral, but are not at all inconsistent with the existence of two different conditions of equilibrium, such as (E_1, E_2) and (E_1', E_2').

Harmonics cannot directly influence the position of the neutral of the fundamental frequency voltages, except indirectly by modifying the character of saturation. Oscillograms of inversion show that the harmonics are of relatively small value and exert no controlling influence on the phenomena.

So far as the effective values of the voltages are concerned, such as measured by r. m. s. voltmeters, harmonics always act as if they were at right angles to the fundamental (and to each other), and thus give an apparent shift to the neutral at right angles to the line voltage, as well illustrated by the laboratory tests.

(*b*) *Inversion in a Three-Phase Circuit.* If the neutral of a Y-Y or Y-broken-delta bank of transformers is grounded on a circuit which is otherwise isolated, the neutral of the transformers is joined to the neutral of the line capacitances to ground, and we have an equivalent circuit such as shown in Fig. 6A. Each leg of this network will have a volt-ampere characteristic similar to Fig. 2, capable of acting either as a capacitive reactance or as an inductive reactance.

Assuming the three legs as duplicates, the normal position of the neutral will be at the center of gravity of the line voltage triangle. However, other positions of equilibrium also exist, as for instance, two of the legs operating in the zone B-D with a lagging power factor, and the third in the zone O-A with a leading power factor, as explained for the single-phase circuit, in which case, one leg will be reversed, the other two will be greatly overexcited, and the neutral will fall outside of the triangle of line voltages. The alternative case, in which all the legs operated capacitively, one in the zone O-A, the other two in the zone A-B, as discussed in connection with single-phase neutral shift, the neutral falling just inside the line voltages, has also been observed.[5]

Since any one of the legs may become underexcited, depending on the instant of switching, there will be at least three abnormal and stable positions of the neutral.

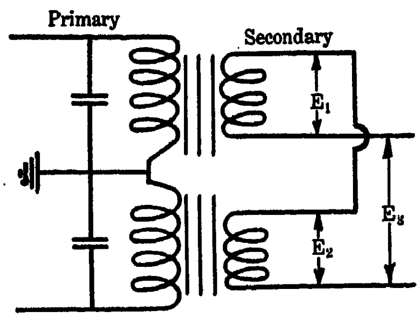


FIG. 4—CIRCUIT CONNECTION FOR SINGLE-PHASE NEUTRAL INSTABILITY TESTS

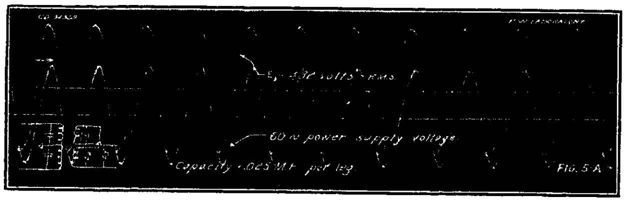
Voltage corresponding to normal neutral is neutralized and eliminated from E_3 which therefore exhibits only shifts and oscillations of the neutral

In the foregoing discussion, it was assumed that two legs may become overexcited, one underexcited. The other alternative, namely, two underexcited and one overexcited, is not ordinarily likely, because, no matter which two legs are considered, they will have to stand the line voltage common to them. If the tests are made at such a low voltage that even with line voltage the density in the two legs is low in the zone O-A; then, for the same reason, it may become impossible to carry the third leg into the high density zone B-D by any switching transient, or find an equilibrium point there.

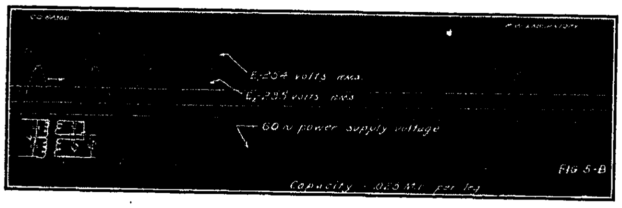
Losses and harmonics may shift somewhat the position of an abnormal neutral, but, unless intensified far beyond usual proportions, will not affect the persistence of an abnormal neutral potential.

Single-Phase Inversion Tests. If the theory of inversion outlined above is true, it should apply to a single-phase circuit as well as to three-phase. To verify this, two duplicate standard potential transformers, rated 13,200 volts to 110 volts, were connected in series to yield a neutral point, as shown in Fig. 4, and each trans-

former was shunted by a variable capacitance. The settings of the capacitances of the two branches were made alike in all cases, so that the potential of the neutral would normally be halfway between those of the terminals. When the circuit was connected to the generator, and the voltage gradually brought up by field control, the neutral was found to be normal in all cases. However, when the generator was first excited to the desired voltage, and the voltage suddenly thrown on the load, inversion of the neutral point was observed over a

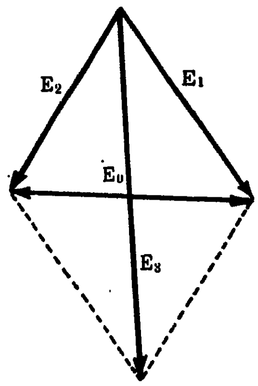


A



B

N



C

Fig. 5
A. and B. Oscillograms of Neutral Shift Taken on Circuit of Fig. 4
C. Vector Plot of A and B

fairly wide range of capacitances, this range depending on the excitation of the transformers.

Referring to Fig. 4, the secondaries (low voltages) of the potential transformers will be seen connected in series opposition. The purpose of this was to segregate the abnormal voltage component of the neutral. Obviously, with balanced branch voltages the terminal voltage of the secondaries (as connected up) would be zero, but if the neutral should shift, invert or oscillate, the phenomenon will then appear in the resultant voltage of the two secondaries in its pure form, unmixed with normal voltages.

With line voltages, representing from 100 to 120 per cent excitation on the potential transformers, the neutral of this single-phase bank would frequently come in inverted, with capacitances from 0.025 to 0.050 μf. across each unit (on the high voltage side). A representative set of readings is as follows:

Table I

Line voltage representing 120 per cent excitation:

E_1	E_2	E_3	Oscillogram	Vector diagram
193%	178%	328%	Figs. 5A, 5B	Fig. 5C

(Note: The voltages are in per cent of the values corresponding to normal neutral).

The oscillograms in Figs. 5A and 5B show that all the voltages are of fundamental frequency and of reasonably good wave shape. Considering the vector diagram in Fig. 5C, the branch voltages are seen as of the same order of magnitude, and that the neutral has shifted almost in quadrature with the impressed voltage. The significance of this is that one of the branches is operating capacitively in the zone *A-B* (Fig. 2) fairly close to *B*, the other inductively in the zone *B-D*, but again fairly close to *B*. Only such a combination will give an inversion in which E_1 and E_2 will be so nearly equal. There were a good many cases of inversion in which the branch voltages were very unequal, but these were usually complicated by superposed oscillations. Inversions with unequal leg voltages, unmixed with oscillations, were more easily obtained in three-phase tests.

It is further to be observed in connection with the vector diagram (Fig. 5C) that the voltage E_3 is vectorially equal to twice the neutral shift, as theory would demand.

Three-Phase Inversion Tests. The circuit utilized is shown in Fig. 6A. It should be observed that when the neutral is normal, the voltage across the corner of the delta will be zero, but when the neutral moves from this position, it will show in the corner of the delta. Thus, the phenomena showing across the corner of the delta are entirely those of zero sequence components: whether they are third harmonic, or something else, is purely incidental. That is, any voltage of any frequency in the leg voltages will show across the corner of the delta if it is of zero phase sequence, and will cancel out if it is symmetrical polyphase. In more common terms, only those phenomena which disturb the neutral can appear across the corner of the delta, all others cancel out. Voltage oscillograms taken at this point, therefore, show clearly the nature of the disturbance of the neutral. The magnitude of this voltage will be three times the corresponding component in each leg.

Data on the typical cases of inversion follow:

TABLE II

1.	Vector diagram of readings, Fig. 6B		
	Oscillogram Figs. 6C, 6D		
	Capacitance 0.020 μf. per leg.		
	Impressed voltage	100	per cent of rating
	Observed, leg 1	96	" " of line voltage
	" 2	110	" " " " "
	" 3	21	" " " " "
	Cor. of delta	190	" " " " "
	" " "	300	" " " neutral shift
2.	Capacitance 0.010 μf. per leg.		
	Impressed voltage	75	per cent of rating
	Observed, leg 1	28	" " " line voltage
	" 2	114	" " " " "
	" 3	103	" " " " "
	Cor. of delta	207	" " " " "
	" " "	300	" " " neutral shift

(Note: Wave shape and vector diagram of case No. 2 were very similar to those of No. 1 and were therefore omitted).

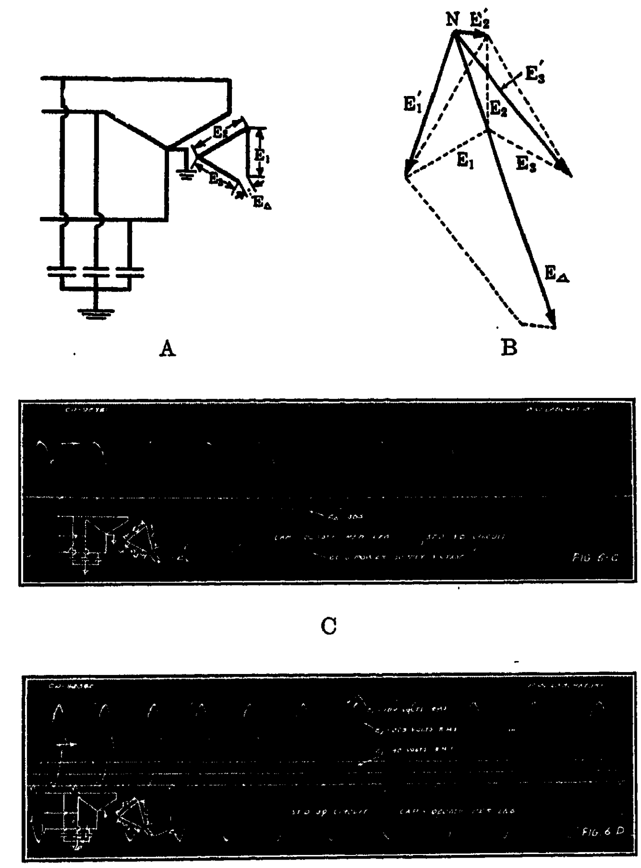
Comments:

1. The oscillograms (Figs. 6C and D) show that the phenomena are of fundamental frequency and of reasonably good wave shape.
2. The data show that two legs are overexcited (acting inductively) and one underexcited (acting capacitively). The fact that the neutral shift is not exactly parallel to the normal leg voltage of the underexcited leg is largely due to the losses.
3. It was observed that any one of the three legs might come in reversed, on switching-in.
4. Inversion did not, of course, take place at every switching-in operation. As the upper or lower limit of the capacitance range was approached (0.005 and 0.020 μf. respectively), inversion occurred less and less frequently.
5. Inversion phenomena were not observed at excitations less than 55 per cent of normal. This figure, however, need not be taken very seriously as we may not have properly exhausted all possible combinations of density and capacitance conducive to inversion, but it is in accord with the theory outlined above that if the densities are kept so low that during switching-in transients the voltage will not go into the zone $A\ B$ (Fig. 2), the neutral should be stable.

OSCILLATING NEUTRAL

When the neutral is disturbed in any way, the transition to a state of equilibrium must take place through an oscillation at the natural frequency of the network. In the group of phenomena classified as inversion of the neutral, this oscillation dies out, and the remaining phenomena are the fundamental frequency currents and voltages, and their usual harmonics. This is beautifully illustrated by the oscillogram in Fig. 7. In many other cases, the oscillation is found to persist.

The Equivalent Circuit of Oscillation. The single-phase network shown in Figs. 3A and 4 has two possible ways of natural oscillation. (1.) The capacitance and reactance of each leg or branch could oscillate against each other, and if the phase of oscillation of one branch or leg is 180 deg. from the oscillation of the other, the neutral will oscillate without showing any oscillation voltage or current in the supply lines. (2.) One leg or branch may show a net inductive reactance, the second, a net capacitive reactance, and thus the neutral may again oscillate without any oscillation voltage in the supply lines, but with an oscillation current in the supply lines. But as the ohmic value of the net effective reactance of each leg for the oscillation increases (by parallel resonance), the current will decrease for a given oscillation voltage. Thus, the difference between 1 and 2 being merely a matter of the magnitude of the oscillation current in the lines, the two types of phenomena are not radically different, but merge into each other, and when the oscillation current in the lines is small, the phenomenon may equally well be considered



A B C D

FIG. 6

A. CIRCUIT USED FOR THREE-PHASE NEUTRAL INSTABILITY TESTS. WITH NORMAL NEUTRAL E_Δ IS ZERO, AND THUS E_Δ EXHIBITS ONLY SHIFTS AND OSCILLATIONS OF THE NEUTRAL

B. VECTORIAL PLOT OF A NEUTRAL SHIFT OBSERVED ON THE CIRCUIT OF FIG. A

C. OSCILLOGRAMS OF NEUTRAL SHIFT TAKEN ON CIRCUIT OF FIG. A

one way or the other. These and other important relations may be illustrated as follows.

In Fig. 8, O-A-B-C is the volt-ampere curve for normal impressed frequency, while O-A'-B'-C' is that for half frequency, and the dashed curve for a multiple of normal frequency. The reader may easily check that the lower frequency curves must fall inside, higher frequency curves outside, of the normal frequency curve. For a given order of voltage, the normal frequency operation may be around A, the half-frequency oscillation around B'. If both units are oscillating corresponding to the point B', we have the oscillation of type 1 mentioned above and a limiting case of type 2. But if one unit is somewhat below B', say at B'', in the condensive zone, while the other is a little above B', say at B'', in the inductive zone, we have an oscillation of type 2 mentioned above. As B'' and B''' approach B', 2 becomes converted into 1 as its limiting case. A consideration of these curves will also indicate that natural frequencies of oscillation compatible with normal frequency excitation should fall in the range of observed oscillation frequencies.

Experience shows two important facts; manely, first, that these oscillations may be loaded with considerable losses and still persist, indicating that they are able to draw a considerable amount of energy from the circuit; and second, that in the simpler cases, with comparatively little wave distortion, the oscillation frequency is seen to be in a zone corresponding to the nearest harmonic relationship; that is, either the second harmonic, or frequently, one-half harmonic, although not necessarily these values exactly. These two facts call for explanations as to how these oscillations can draw power from the impressed frequency, and how the 2 to 1 or 1 to 2 (that is, even harmonic) relationship can be maintained without direct current excitation.

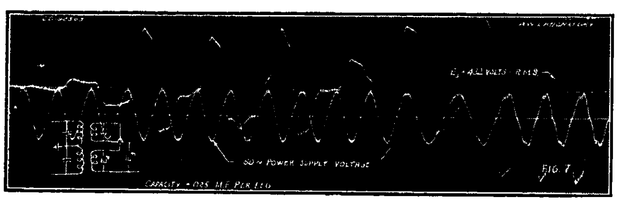


FIG. 7—OSCILLOGRAM OF SINGLE-PHASE NEUTRAL INSTABILITY EXHIBITING AN INITIAL OSCILLATION AND GRADUAL TRANSITION INTO INVERSION

FLOW OF POWER FROM ONE FREQUENCY TO ANOTHER

To consider a well-known case, Fig. 9 shows a static frequency converter, converting from an impressed frequency to its triple frequency. The production of third harmonic voltage by saturation and by suppression of third harmonic exciting current is too well known to require any proof or explanation here. The loading characteristics of the third harmonic circuit depend on its no-load voltage and short-circuit current and may be represented reasonably well by the conventional circle diagram. By using higher and higher values of saturation, both the no-load voltage and the short-circuit current and hence the maximum output of the triple frequency side, are increased. For instance, at nominal 60-cycle densities around 170 kilolines per sq. in., third harmonic outputs over 100 kw. per thousand lb. of core can be obtained. Of course, the corresponding amount of power (plus the high losses) flows from the primary mains into the primary windings at fundamental frequency.

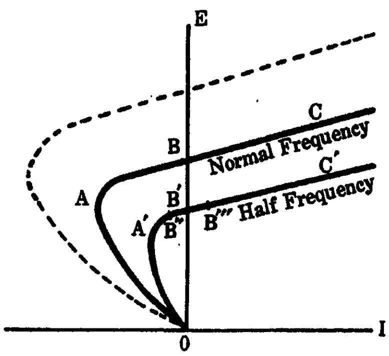


FIG. 8—CHARACTERISTIC MODIFICATION OF FIG. 2, FOR VARIOUS FREQUENCIES

Energy flow from one frequency to many other frequencies besides the third, is also possible. For instance, second harmonic. This, however, requires that the core be biased, a condition easily brought about by d-c. excitation.

Very large amounts of power at double frequency may be drawn from a static frequency multiplier at low nominal 60-cycle excitations, with the aid of a high d-c. excitation.

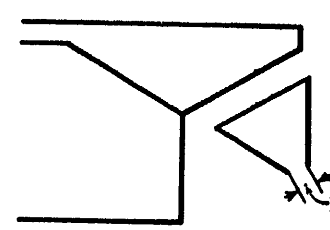


FIG. 9—STATIC FREQUENCY CONVERTER. E_Δ IS A REASONABLY PURE TRIPLE FREQUENCY VOLTAGE

REVERSIBILITY OF POWER FLOW

The flow of power in a frequency multiplier from a lower frequency to a higher frequency must be reversible.

Assume that I_3 is the current in a certain third harmonic load, drawing from the transformer a power P. If the current I_3 is reversed by the application of a suitable third harmonic voltage into the third harmonic circuit from an external source, the power P must also be reversed, delivering power to the transformer instead of drawing power from it. We are, therefore, justified in postulating that power may flow not only from a

fundamental to its harmonics (by virtue of saturation), but that it may also flow back from the harmonics to the fundamental, if the harmonics have access to a suitable external source of supply.

When the reversibility of power flow is recognized, the arbitrariness of calling the lower frequency fundamental becomes obvious. When power is flowing from 180 cycles to 60 cycles, we would be entirely justified in calling the 180-cycle circuit primary fundamental, and the 60-cycle circuit secondary one-third harmonic. But, aside from use of words, it should be obvious that if power may flow from 180 cycles to 60 cycles, it may also flow from 60 cycles to 20 cycles, or from a *fundamental to a subnormal harmonic*, under a suitable circuit condition.

One of the important features of those suitable circuit conditions is that the lower frequency should be able to take care of its magnetizing current, drawing it either from a generator or from a capacitor.

If the impressed frequency and the oscillation are related to each other as a fundamental and an exact harmonic, whether as higher or lower harmonic, the availability of energy to sustain both circuits may be granted in the light of the foregoing.

If the harmonic ratio is even, a source of bias is implied and must be accounted for; and, if the higher frequency is not an exact multiple of the lower, the possibility of sustained power flow from one frequency to the other must be accounted for.

Even Harmonics and Source of Bias

In the absence of sustained direct current, an available source of bias is residual. The direct current component of the switching transient might well start even harmonic oscillations, but as this direct current must soon die out, while the oscillations persist indefinitely, residual might sustain the bias.

We are accustomed to believe that an unexcited transformer core may carry a residual flux in it indefinitely, but that when an alternating flux is superposed on it, the residual must decay. It appears, however, that under favorable conditions the residual flux might persist; favorable conditions being those in which an even harmonic is capable of self-excitation by drawing its magnetizing current from an oscillating circuit and losses from a primary circuit. In view of the fact that the persistence of residuals under any condition, and decay under any other condition, are empirical facts, we need not speculate here on their theoretical explanations, but may well be satisfied with the observation of the mathematical fact that the superposition of two harmonic fluxes, having an even frequency ratio, makes the positive B_{max} different from the negative B_{max} in the core, as if the zero axis has been shifted. This fact may favor the persistence of a residual.

Non-Integral Ratios

Since the natural frequency of oscillation of the circuit is independent of the impressed frequency, the oscillation need not bear an integral ratio to the impressed frequency. In the majority of the cases produced in the laboratory, the frequency ratio was not an integer, and, there was a continuous phase shift between the impressed voltage and the oscillating voltage. A permanent residual can not, of course, support such an oscillation—the bias must also shift phase; that is, it must be an alternating bias at the heterodyne beat frequency. Saturation leads to the production of such alternating bias by modulation when fluxes at two different frequencies are combined in one core. The principle that saturation will cause modulation under such conditions, has already been commercially made use of by Mr. Alexanderson in his well known "magnetic amplifier." Oscillations of the neutral practically always show such low frequency components in the waves and in the accompanying noises and flickers.

If the natural oscillation at approximately even frequency ratio continually shifts phase with respect to

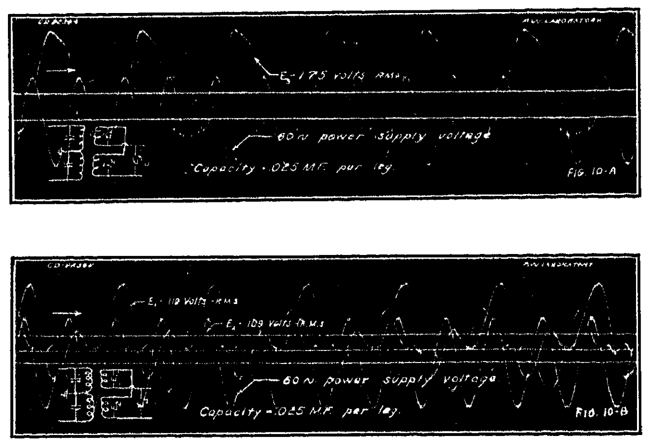


Fig. 10—Oscillograms of Oscillating Single-Phase Neutral

the impressed frequency, it cannot draw power from the impressed frequency uniformly, but must rise and fall. If the power flow were dependent exclusively on a fixed residual, the power flow to a shifting oscillation should not only pulsate but should also reverse; but, if dependent on a low frequency, alternating bias, then it need not reverse even though it must pulsate.

Harmonics of Natural Oscillations

It is to be expected that in the presence of saturation, not only the impressed frequency currents and voltages may become distorted and be given higher harmonics, but the oscillation of the network may also become distorted and be given higher harmonics. An oscillation at half impressed frequency may have a third harmonic of its own, and this will obviously appear as a one-and-a-half harmonic for the fundamental. Consequently, when a complex wave is being analyzed, confusion may arise by attempting to resolve everything into harmonics of the impressed frequency. Fortunately, many instances are found

in which the secondary harmonics of both the impressed frequency and the oscillating frequency are small, and by suitable arrangement the oscillation can be segregated and shown to be of surprisingly good wave shape, as discussed below.

Single-Phase Tests of Oscillating Neutral

Case 1. Fig. 7 illustrates perfectly how the transition from the initial unstable condition to the final

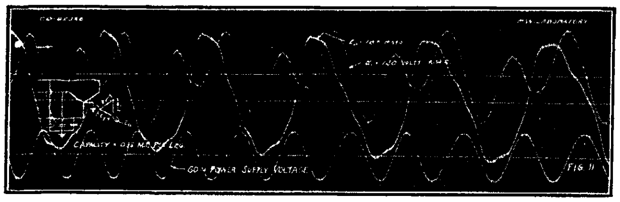


Fig. 11—Oscillogram of Oscillating Three-Phase Neutral

inverted condition of the neutral takes place through a series of gradually intensified natural oscillations at approximately half the impressed frequency. In this instance, the oscillations gave way to inversion, but in range of capacitance values above 0.025 μf. up to 0.050 μf., the oscillations once started usually persisted.

Case 2. Figs. 10A and 10B illustrate a case in which the oscillation persisted indefinitely. Note how remarkably pure is the wave shape of the oscillation of the neutral (single-phase neutral), and how the oscillation frequency is exactly one-half of the impressed frequency.* Examining the waves of the leg voltages (E_1 and E_2) nothing else of importance is found in them but a fundamental and a half-frequency harmonic. The flicker in the lamps connected across each phase was of comparatively high frequency, according to the oscillograms.

The indicated range of capacitance (0.025 to 0.050 μf.) was found to be adequate to furnish the necessary magnetizing current for the oscillation.

Examination of the oscillation on a long film does not reveal any definite pulsation in its amplitude. This is consistent with the integral ratio of the oscillation.

Tests with single-phase neutral oscillation were made primarily to verify the theory that the peculiar phenomena observed in three-phase circuits are not due to any virtue inherent in three-phase connection, but that they could occur in any circuit consisting of members with characteristics such as shown in Fig. 2. Having established this point both with reference to inversion and to oscillations, tests with single-phase circuits were not carried much further.

Tests with Oscillations of Three-phase Neutral

The circuit connection for neutral oscillation was the same as for inversion (Fig. 6A), the phenomena changing from one type to the other in going from one capacitance range to the other. The two ranges of capacitance overlap, and so do the phenomena.

a. Similarity to Single-Phase Tests. Fig. 11 gives the timing wave (supply voltage), leg voltage, and the neutral voltage for a typical case of oscillation. The neutral voltage is observed across the corner of the

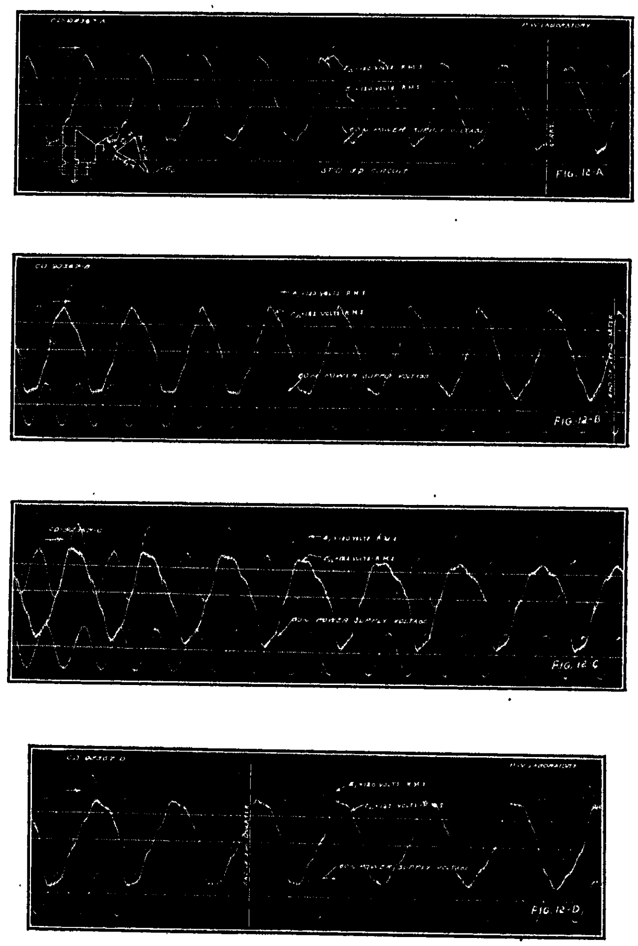


Fig. 12—Oscillograms of Three-Phase Neutral Showing One-Half Harmonic Oscillation with a Slow Phase Shift with Respect to Supply Voltage

delta. The characters of these waves will be seen to be substantially the same as in the single-phase tests: the three-phase connection has not materially modified the phenomena.

b. Continuous Phase-shift. While in the single-phase test, one leg oscillates against the second leg; in the three-phase case one leg oscillates against the other two in parallel. This has made enough change in the constants of the oscillating circuit so as to make

*The reason for the comparative simplicity of wave shapes observed in these tests was the fact that the circuit was made resonant for a subnormal frequency and would therefore not appreciably affect the higher harmonics of the magnetizing current. If the capacitance had been adjusted for oscillation at double normal frequency, it would have been near enough to third and fifth harmonic resonance to intensify them a great deal and, thereby lead to a very complicated wave shape, as had been observed by a number of the investigators. No attempt was made in this investigation to reproduce double or higher frequency oscillations, since the nature of the phenomena could be studied more conveniently at the lower frequencies.

its frequency definitely different from half of impressed frequency, and consequently we observe (in the long film, Fig. 12) a slow continuous shift of phase of neutral oscillation with respect to the leg voltages and to the timing wave. Examining the leg voltage, we see that it contains nothing else of importance but the impressed frequency and the oscillating frequency. Furthermore, we see that due to the continuous phase shift

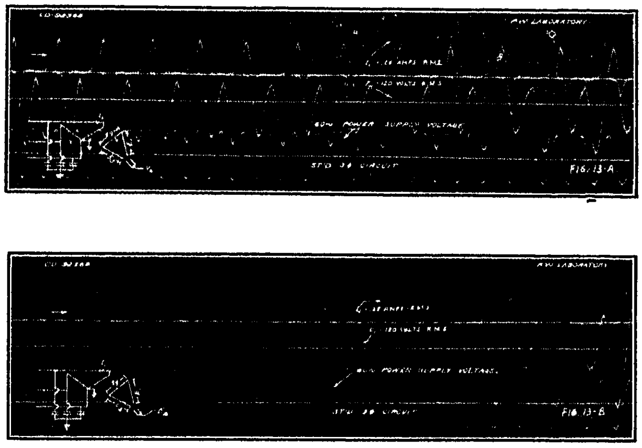


Fig. 13—Oscillogram of Three-Phase Neutral Oscillating at Half-Frequency Combined with a Small Normal-Frequency Neutral Shift

Note the characteristic shape of the exciting current I_L for this condition

between these two components, the wave shape of the resultant leg voltage continually changes, repeating at a low beat frequency. On Fig. 12, the oscillation frequency is seen to be 0.48 of the impressed frequency, producing one beat cycle every 50 cycles of the impressed frequency. Quarter periods of this beat cycle are shown in Fig. 12 by means of vertical lines. This period varied, of course, a great deal with varying circuit constants, as follows.

TABLE III

Excitation	Capacitance per leg	Beat frequency cycles per sec.	Capacitance per leg	Beat frequency cycles per sec.
120 per cent	0.045	0.53	0.025	0.33
100 " "	0.045	0.50	0.025	. .
90 " "	0.045	0.57	0.025	0.33
82 " "	0.045	0.67	0.025	0.40
73 " "	0.045	1.00	0.025	0.53

c. Peculiarities in the Transformer Exciting Current. Considering the current in each transformer primary (I_L in Fig. 13), the curious fact is observed that in certain zones of the film this current is negligible for a whole cycle of impressed frequency, and two appreciable peaks for the adjacent cycles of the impressed frequency. Other peculiar wave shapes will be seen in other zones. These are very easily explained by combining two fluxes of fundamental and half frequency together (in various phase relationships) and plotting the corresponding magnetizing current: the characteristic wave shapes in the different zones will all be reproduced.

d. The Capacitor Current. Considering the current in the capacitors (I_c Fig. 14), it is seen to contain three components: (1), a fundamental, (2), a half frequency, and (3), a small high frequency ripple. It will be further observed that the ratio of the half-frequency component to the fundamental is a great deal less in the current, than in the voltage wave, as it should be, theoretically, one-half.

e. Effect of Extraneous Capacitances. To make certain that extraneous capacitances to ground were not influencing the phenomena more prominently than those which were deliberately connected into the circuit, comparative tests were made with the neutral alternately grounded and isolated, and the conclusion was drawn that these concealed capacitances did not exceed 10 per cent of the main capacitances.

f. Variation in the Intensity of the Oscillation. Fig. 12 shows that the amplitude of the oscillation varied at the slow beat or modulation frequency. This is in accordance with theory, but one may wonder why the variation is not larger. The reason for it probably is that the power factor of the oscillation is very low: the hysteresis loss is largely furnished by the impressed (higher) frequency, while the eddy current loss is one quarter of that at impressed frequency.

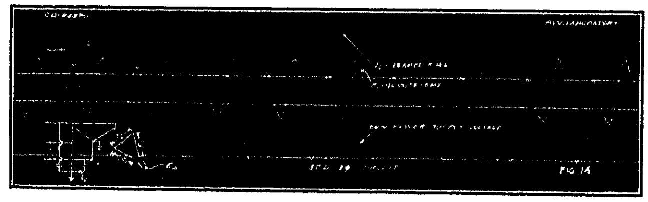


Fig. 14—Oscillogram of Capacitor Current and Capacitor (Leg) Voltage under Conditions of Fig. 13

g. Amplitude of the Oscillation. Some of the data are tabulated below:

TABLE IV
VOLTAGES IN THREE-PHASE TESTS

Test freq.	Cap. µf.	Fund. per leg volts	Osc. per leg volts per cent		Complex wave Measured volts	Complex wave Calc. volts
50	0.035	92	42	45.5 per cent	100	101
60	0.045	80	81.3	102 per cent	112	114
"	"	90	79	88 " "	118	120
"	"	100	75	75 " "	123	125
"	"	110	71	65 " "	126	131
"	"	120	62	52 " "	135	135
"	"	130	53	41 " "	140	140
"	"	140	43.5	31 " "	145	146
"	0.025	80	70	87.5 per cent	105	106
"	"	90	66.5	74 " "	111	111
"	"	100	61.5	61.5 " "	115	117
"	"	110	53.5	48.5 " "	122	122
"	"	120	43.5	36 " "	128	128

Some of the more interesting features of these data are:

1. Oscillation voltages of the same order of magni-

tude as the impressed frequency voltages are observed. Curiously enough the higher oscillation voltages have taken place at the lower excitations close to the border where the oscillation would stop altogether. With varying capacitances also, the higher oscillation voltages occurred close to the limiting value of capacitance at which the oscillation would stop altogether. In single-phase tests oscillations as high as 117 per cent of fundamental were observed. In either case, no effort was made to produce the maximum possible amplitude of oscillation.

2. The amplitude of the oscillation per leg was determined by taking one-third of the voltage across the corner of the delta. The fundamental was obtained from the line voltages. There is good agreement between the measured values of the complex voltage per leg and the corresponding values calculated with the aid of the two components.

h. Comparison of Wave Shapes of Three Legs. Fig. 15 shows the three leg-voltages. The differences in wave-shape are due to the fact that while the oscillation voltage is of the same magnitude and phase in all three legs (as a zero phase sequence phenomenon), the impressed frequency voltages are 120 deg. away from each other and therefore combined with the oscillation voltage at different phase angles. The wave shapes A, B, C, of this figure are reproduced by A', B', C' in Fig. 16, by combining with a given half frequency oscillation three fundamentals spaced 120 deg. away from each other.

Damping the Oscillations

Since the oscillation, unmixed by impressed frequency, appears only across the corner of the delta, the loading of the oscillation (without loading the impressed frequency) was done by connecting an adjustable rheostat at that point. This rheostat, however, was not the only load; the voltmeter and the ammeter were additional loads, besides the internal losses of the oscillating outfit. The data follow:

TABLE V

CAPACITANCE PER PHASE 0.035 μf.

Excitation on lines	Oscillatory watts in external load to stop oscillation	Equivalent watt rating of load per phase (See note below)
140 per cent	0	0
130 " "	2	..
118 " "	25	87
113 " "	35	79
109 " "	49	91
100 " "	68	96
91 " "	78	63
82 " "	78	15
72 " "	67	11
64 " "	47	8
55 " "	3	..
50 " "	0	0

(The column headed "Equivalent Load per Phase" gives the watts that would have been drawn per phase at impressed frequency if the damping resistances had been connected across each phase, instead of across the corner of the delta).

It is seen from the above data that less loading is necessary at the lower densities to damp out the oscillations. The reason for this is not that the oscillations are weaker, but rather that the magnetizing volt-amperes are very much smaller at the lower densities and, therefore, a smaller load brings up the power factor of the oscillating circuit to the necessary value. As a general conservative estimate, we would be inclined to suggest that the loading be at least equal to the magnetizing volt-amperes of the transformer. At densities 50-60 per cent of normal, this would constitute no hardship, whether the resistance is connected across the opened corner of the delta or line to neutral. The minimum resistance across the corner of the delta in these tests was about 375 ohms. In cases where potential transformers with line-to-line rating are connected line-to-neutral, operating at 57.7 per cent density, relay and other possible useful loads connected line-to-neutral (or across the corner of the delta) may almost accomplish this damping service.

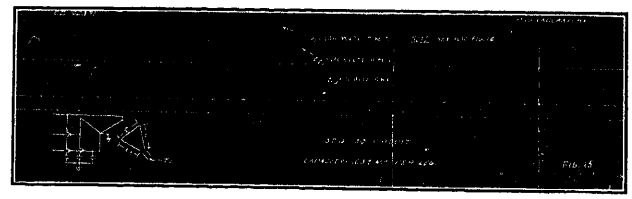


Fig. 15—Oscillogram of Three-Phase Leg Voltages Under Condition of Oscillating Neutral

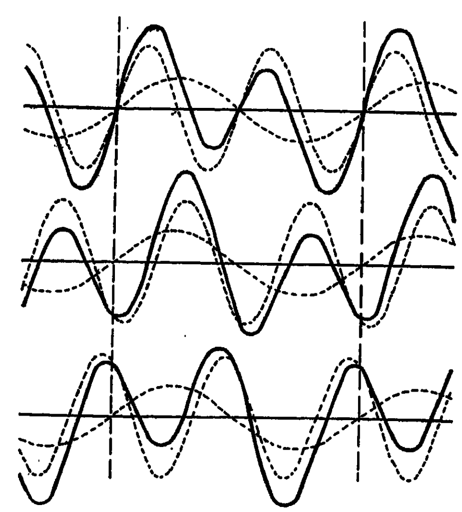


Fig. 16—Graphical Resolution Showing the Fundamental and Half-Harmonic Components of the Three-Leg Voltages of Fig. 15

Strange though it may sound, potential transformers with high quality low loss materials may give more trouble in this respect than those with inferior quality of materials.

Both theoretically and from foregoing test data, units operating at 50 per cent density appear safe from oscillations, but the margin of safety is small and we would doubt the wisdom of omitting all protection by merely going 10 to 15 per cent lower in density (as compared with 57.7 per cent excitation), because the

line voltages may sometime rise that much and wipe out the margin of safety.

Since the present investigation has concerned itself largely with the lower frequencies of oscillations, and since higher frequencies are also possible, question may arise as to the applicability of the present damping data to them. We believe such application would be on the safe side in view of the generally recognized fact that circuits are usually associated with higher losses and damping at higher frequencies.

In considering different methods of applying damping or balancing loads (such as across corner of delta, or line to neutral, or through an auxiliary low-voltage Y-delta potential transformer bank connected to the low side of the high-voltage potential transformer bank) the effect of such loads on metering accuracy is also to be considered, if metering is contemplated.

Conclusions

1. Operation of potential transformers in Y-Y with neutral grounded on an otherwise isolated system (whether permanently or occasionally isolated system, or section of a system) is a somewhat questionable practise unless protective measures are used. With many miles of lines connected to the potential transformers the line-to-neutral capacitances may be large enough to short-circuit all harmonic phenomena, especially in the higher voltage circuits, but when the connected portions of the lines are shortened in length by (temporary) isolation, various kinds of trouble may be anticipated. Systems which are using such connections, may be harboring a possible source of hazard to their equipment.

2. A well-known source of trouble is third harmonic voltage intensification, not discussed in the present paper because it is so well known.

3. It is found that with favorable capacitance values from line to ground, natural oscillations are possible around half normal frequency, as well as double normal frequency. The ratio need not be integral, in which case there is a continuous phase shift between the impressed frequency waves and the natural oscillation frequency waves, resulting in beats and pulsations, due to modulation by saturation.

4. Aside from oscillations, there is the possibility of the inversion of the neutral. The limiting values of resulting overvoltages in both of these cases, were not determined as they were unsafe for the equipment.

5. The explanation of the neutral shift or inversion is based on the fact that the combination of a saturable inductance and a constant capacitance has a multi-valued characteristic curve, with leading and lagging zones. If one leg operates in a leading zone, the other two in a lagging zone, the potential of the neutral is thrown outside of the triangle of line voltages. If all legs operate in leading but different zones of the characteristic curve, the neutral is again shifted but falls just inside the line voltage triangle. Losses and harmonics give a small quadrature shift to the neutral.

6. The persistence of oscillations is accounted for as follows: It is noted that the oscillations satisfy or approximate harmonic relationship to the impressed frequency. When the oscillation is at a higher than impressed frequency, the energy flow to it is similar to that from fundamental to higher harmonics as in static frequency multipliers. When the oscillation frequency is lower, such as one-half of the impressed frequency, the impressed frequency stands in the relationship of a higher harmonic of the oscillatory frequency, and the energy flow is reversed because the location of power and load are interchanged.

7. In potential transformer banks intended exclusively for relaying purposes, the secondary (or a tertiary) could be connected in delta (closed through a resistance just high enough to protect the bank from burnout in times of line-to-neutral short circuits), and then troubles due to either inversion or oscillation would be entirely eliminated. However, if the bank is to be used for metering as well as for relaying, currents circulating in the delta due to unbalanced line-to-neutral conditions in the system may adversely affect the metering accuracy of the outfit.

8. Loading the potential transformer from line to neutral also tends to stabilize the neutral and prevent inversion and oscillations; but, then of course, this will be a constant load at impressed frequency. It is believed that such a load should be at least of the same order of magnitude as the magnetizing volt-amperes of the transformers at normal operating voltage.

9. Operation of potential transformers approximately at half rated voltage is found to reduce greatly the chances of self-excited oscillations. The damping load, equal to the magnetizing volt-amperes at such low excitations, is very small and well worth while. Low density operation and protective load are also desirable from the standpoint of third harmonic phenomena.

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3. "On Phenomena of Self-Excitation in Systems with Disturbed Superposition," Kurt Heegner, *Teitsch. f. Physik* 29, 1924, p. 91.

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5. C. T. Weller. loc, cit.

Discussion

For discussion of this paper see page 342.

Theory of Abnormal Line-to-Neutral Transformer Voltages

BY C. W. LAPIERRE*

Associate, A. I. E. E.

Synopsis.—The abnormal voltages considered here are due to the occurrence of a large harmonic of fractional, even, or odd frequency in the line-to-neutral voltages of certain Y-connected transformer circuits. These phenomena were first described before the Institute in 1915, and other papers on the same subject have appeared since. The results of a detailed study of the instantaneous currents, voltages, and transformer flux densities in the type of circuit involved are presented in this paper. From this study the origin and characteristics of the abnormal voltages have been deduced.

In general the voltages are found to be self-excited by successive alternate saturations in the transformer cores. The first saturation, which starts the phenomena, occurs within one cycle after the voltage is applied, due to the starting conditions of voltage and residual core density. When coupled with the system capacitance in the circuit of this discussion, each saturation establishes the condition for producing a succeeding and alternate saturation so that the process is self-continuing.

The frequency of the harmonic voltage generated by a succession of alternate saturations is dependent only upon the rate at which they occur. It is not surprising, therefore, that harmonics of unusual frequencies have been observed. The wide variations between the initial core conditions in the three transformers result in highly irregular saturations and correspondingly irregular voltages at the start. Such irregularities are of a transient nature. The occurrence of a sustained harmonic voltage is dependent upon the formation of proper multiple saturations which have been found to possess the necessary stabilizing properties. Such stabilizing multiple saturations only occur, for harmonic voltages having a frequency of either one-half, equal to, double, or triple the supply voltage frequency. Consequently, these are the only frequencies which can occur in the sustained condition.

The minor characteristics of the observed data, such as the wave shape, magnitude, and phase of the currents and voltages, beat frequencies, etc., have a definite place in the complete theory.

The present paper is one of a group of three presented at this time. The others, one by C. T. Weller and one by A. Boyajian and O. P. McCarty, cover different aspects of the same phenomena.

INTRODUCTION

THE abnormal voltages considered in this paper are due to the occurrence of a large harmonic of fractional, even, or odd frequency in the line-to-neutral voltages of certain Y-connected transformer circuits. These phenomena were first described before the Institute by L. N. Robinson[1] in 1915. Other papers on the same subject have appeared since, namely, a second one by Robinson[2] and those of King E. Gould[3] and Wilhelm Lampert.[4] These present results of a general nature from a wide variety of observations.

At this time three additional papers on the subject are being made available. C. T. Weller[5] is presenting specific data from an unusually complete series of field observations. A. Boyajian and O. P. McCarty[6] are presenting data from laboratory tests together with a descriptive interpretation of some phases of the phenomena. In the present paper a complete theory of the abnormal line-to-neutral voltages is developed which explains their fundamental origin and their detailed characteristics such as wave shape, magnitude and frequency.

THE ABNORMAL VOLTAGES

The circuit in which the abnormal voltages occur is represented by Fig. 1A. This circuit consists of a Y-connected bank of single-phase grounded-neutral transformers connected to an ungrounded source of supply. Three capacitors represent the capacitance of lines, bushings, etc., to ground. The three-phase line-to-line voltages are fixed by the source and may be assumed balanced and sinusoidal. The transformer or line-to-neutral voltages contain the large harmonics which have been observed. Thus the abnormal voltages are a peculiarity of only that portion of the circuit shown by Fig. 1A and do not involve the supply voltages which are independent and fixed. The transformer secondaries also contribute nothing toward

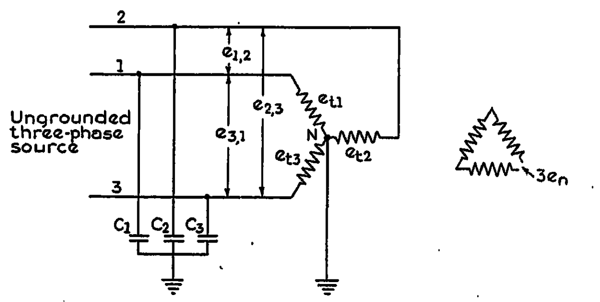

FIG. 1A—REPRESENTATIVE CIRCUIT

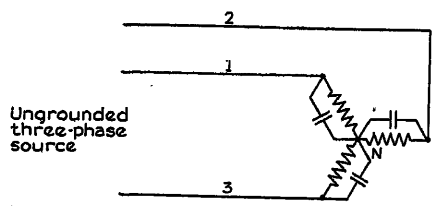

FIG. 1B—SIMPLIFIED REPRESENTATIVE CIRCUIT

starting or maintaining the phenomena, as they have often been open-circuited while the abnormal voltages were being observed. Finally, the various observations have been made with a wide variety of Y-connected single-phase transformers, and in general no special importance can be attached to any particular type or rating.

*General Engineering Laboratory, General Electric Company, Schenectady, N. Y.

1. For references see Bibliography.

Presented at the Southern District Meeting No. 4, of the A. I. E. E., Louisville, Kentucky, November 19-22, 1930.

The large harmonics which occur are abnormal with respect to magnitude and frequency. The resulting transformer voltages may be as much as three or four times normal; consequently, the subject is of importance from the standpoint of insulation as well as operation. Some of the harmonic voltages occur at frequencies which are very unusual if not totally unexpected in ordinary alternating current circuits. In the transient state the voltages are usually very irregular and have no definite frequency. In the sustained condition, the frequency of the harmonic voltage has been found to be either one-half, equal to, double, or triple the supply voltage frequency. Two such frequencies do not occur simultaneously. While the harmonic voltages themselves are not purely sinusoidal, it is significant that other frequencies have not been observed to predominate in the sustained condition. In particular installations it was often found that the mere opening and closing of the supply switch would change the frequency of the predominant harmonic.

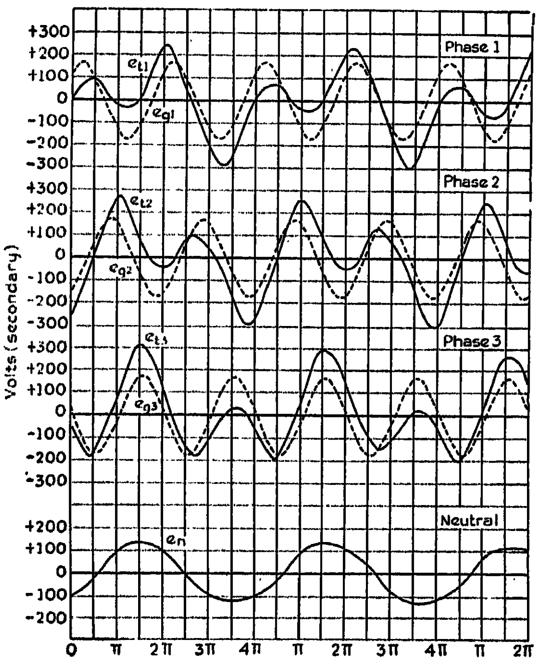

FIG. 2—HALF FREQUENCY NEUTRAL VOLTAGE

$e_t = e_n + e_g$

In Figs. 2, 3, 4, and 5 the above frequency conditions are illustrated by reproductions and derived curves from oscillograms obtained by C. T. Weller.[5] Other illustrations are given in his paper where harmonic voltages of one-half, equal to, double, and triple the supply voltage frequency have been designated phenomena *C*, *A*, *B*, and *D* respectively. A. Boyajian and O. P. McCarty[6] have segregated the phenomenon of equal to system frequency and designated it "neutral shift or inversion." All of the other frequencies which occur are termed by them "oscillation of the neutral." This classification arises from the fact that the voltage relations in the one phenomenon can be described by means of a conventional vector diagram, whereas the others cannot.

In addition to the characteristics discussed and illustrated above, a low frequency audible beat of from a fraction to one or two cycles per second is associated with the one-half and double frequency phenomena in three-phase circuits. Oscillograms with condensed time axis confirm these beats as variations in the currents and voltages within the transformers. As a result of the beats, the one-half and double frequency phenomena do not have exactly these relations to the supply frequency, but differ therefrom by a small amount.

SELF EXCITATION OF THE ABNORMAL VOLTAGES BY SUCCESSIVE ALTERNATE SATURATIONS

For the purpose of describing the phenomena it has been desirable to classify the abnormal voltages according to whether they are transient or sustained and, in cases of the latter, according to frequency. Regardless of the various classifications, it has long been recognized or assumed that they have a common origin, namely, that all are the result of saturation* in the transformer cores. For the time being, therefore, it is desirable to forget the various classifications and to investigate the circuit of Fig. 1A with a view toward determining its properties under conditions of transformer saturation, rather than for the purpose of explaining a particular set of voltmeter readings.

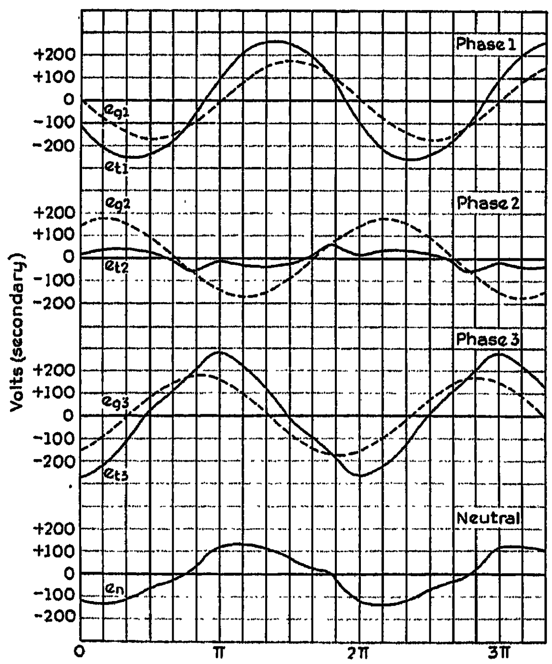

FIG. 3—FUNDAMENTAL FREQUENCY NEUTRAL VOLTAGE

$e_t = e_n + e_g$

*By saturation is meant the operation of a transformer at flux densities on or above the knee of the magnetization curve. The term thereby includes quite a wide range of possible densities, each being associated with a current much larger than the normal excitation current of the transformer.

Of primary importance in Fig. 1A are the relations between the various voltages. The abnormal conditions which occur are the result of harmonics in the voltages across the individual transformers. These harmonics have zero phase sequence and do not appear in the line-to-line voltages which are fixed by the source. In other words the three harmonics are identical in phase and magnitude and must cancel when any two transformer voltages are combined to give the corresponding line-to-line voltage. Thus the harmonics are in reality only a single component appearing in each of the three transformers. Since the component is the voltage by which the neutral differs from its normal or zero value, it may be termed the neutral voltage.* Neutral voltages, for some examples of the phenomena under discussion, are shown in Figs. 2, 3, 4, 5, and 13.

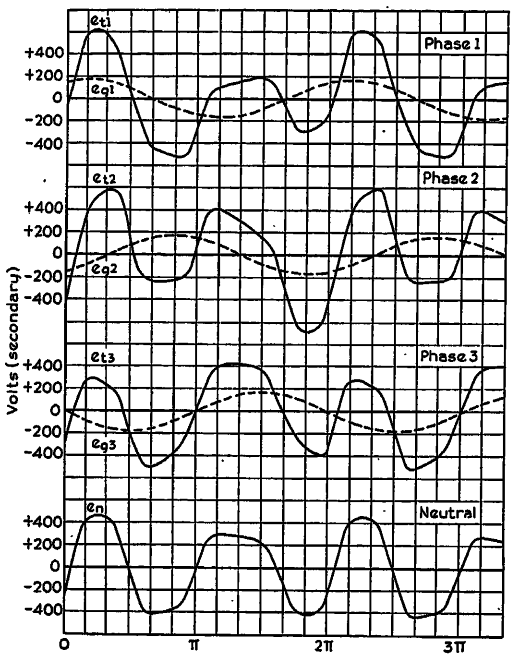

FIG. 4—DOUBLE FREQUENCY NEUTRAL VOLTAGE

$e_t = e_n + e_g$

The neutral voltage is not directly related to the source, and its magnitude and frequency are not necessarily determined by the supply voltages. A discussion of its variations must, therefore, be based upon instantaneous values, since average or effective values have no physical significance in themselves but are only applicable to voltages of known wave shape. Then too, the transformers operate over such a wide range of flux densities that their instantaneous inductance values may lie any where within a range corresponding roughly to the ratio, 5,000 to 1. It is difficult to conceive of an average or effective value which could possibly represent such a variable inductance.

*The neutral or harmonic voltage at any instant may be calculated by adding the instantaneous line-to-neutral voltages and dividing by three. The normal voltage components always add to zero leaving three times the neutral voltage. The addition may be physically accomplished by connecting the secondaries as shown in Fig. 1A and measuring three times the neutral voltage across the broken delta.

Consequently, the theory of this paper is based upon the results of a detailed study of instantaneous voltages, currents, and flux densities in the circuit of Fig. 1A. The study consisted of a series of computations making use of the known relations existing between the fundamental constants and variables in any circuit containing inductance and capacitance. Each computation started by assuming a source of sine wave three-phase voltages applied to the circuit of Fig. 1A at a chosen instant. This was followed by simultaneous consideration of the three variables of each transformer, namely, voltage, current, and flux. Although the step-by-step computations are tediously long, the actual transient and sustained voltages may be determined in this manner. However, with several such computations as a background the relatively few basic principles involved in the phenomena have been deduced. It is only necessary to establish these basic principles, for by their application all of the characteristics of the phenomena may be adequately explained. In the paragraphs immediately following, the theory is outlined and its basic principles introduced. A more complete discussion of the various factors involved is contained in the later sections of the paper.

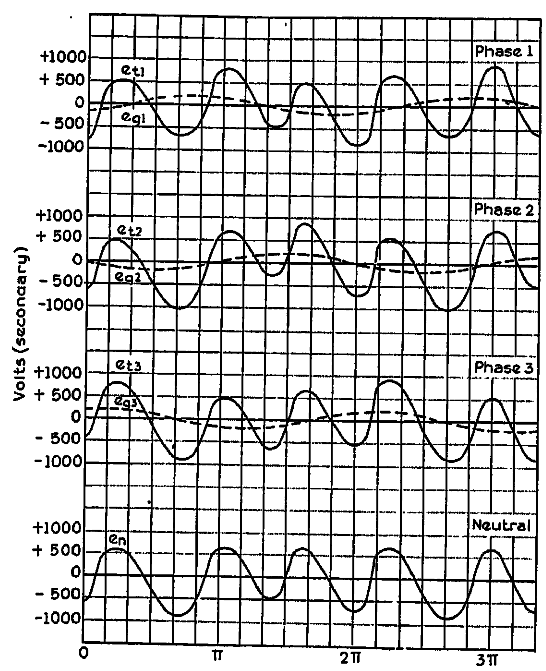

FIG. 5—TRIPLE-FREQUENCY NEUTRAL VOLTAGE

$e_t = e_g + e_n$

The voltages shown have not quite reached the steady state

Although Fig. 1A represents the circuits in which the phenomena have been observed to occur, the circuit of Fig. 6A may be expected to produce the same transformer voltages and is identical in that respect to Fig. 1A under certain conditions. (See Appendix). In

Fig. 6A the capacitor voltage is equivalent to the neutral voltage defined above, and may be visualized directly without the necessity of separating it from the transformer voltages as is the case in Fig. 1A. It is the variation in the voltages across this capacitor which introduces the harmonics in the transformer voltages. Furthermore, in Fig. 6A, the capacitor or neutral voltage is the only voltage that must be determined. All of the others are related to it and the

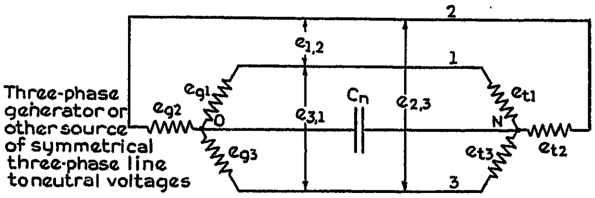

FIG. 6A—EQUIVALENT CIRCUIT

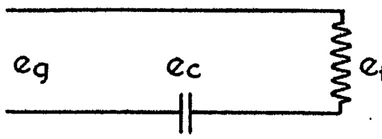

FIG. 6B—SINGLE-PHASE CIRCUIT

known supply voltages by the simple algebraic formulas,

$$\left.\begin{aligned} e_{t1} &= e_n + e_{g1} \\ e_{t2} &= e_n + e_{g2} \\ e_{t3} &= e_n + e_{g3} \end{aligned}\right\} \qquad (1)$$

The validity of these equations is evident when the voltages in each of the closed circuits are traced out.

Thus by adopting a particular type of supply, it is possible to reduce the problem to a consideration of the voltage across a single capacitor. While it is theoretically immaterial which figure is used in the following discussion, the processes to be described will have far greater practical significance if they are based upon Fig. 6A.

The Origin of the Abnormal Voltages. Saturation during the first cycle after connecting a transformer to a source of voltage is a common occurrence. Such saturations are the result of initial conditions of voltage and residual core densities. In transformers connected directly across a single-phase supply, the initial saturation results in the familiar starting currents represented by Fig. 7. This curve actually consists of a succession of saturations, all in the same direction. The magnitude of the peaks gradually diminish until normal densities are not exceeded. Each saturation is an individual event consisting of a rise of the current and flux along the hysteresis loop of Fig. 10 and their subsequent decay to normal values. The large current accompanying a single saturation is unidirectional; it cannot become a large reversed current until after the core density reaches saturation values in the opposite direction.

Referring to Fig. 6A (or Fig. 1A), assume the chance occurrence of a single saturation a short time after the supply switch is closed. The resulting unidirectional current must flow into the system capacitance since the unsaturated transformers will not pass an appreciable part of this current. The current flowing into the capacitance builds up a unidirectional capacitor voltage. This voltage continues to rise until the cycle of saturation is completed, at which time the transformer is restored to normal densities. With all of the transformers at normal densities, their impedances are too high to permit the capacitor to be discharged. Consequently, the capacitance voltage will be maintained practically constant for the time being. This action of a single saturation in the circuit is not unlike that of a valve. It injects a large current into the capacitance and then closes the entrance path to prevent its discharge. The magnitudes of the various changes resulting from a single saturation are dependent to a large extent upon the circuit constants, such as capacitance, normal transformer flux densities, size of core, number of turns, etc. It is not necessary to consider these factors at the outset, as the fundamental nature of the phenomena may be explained on the assumption that a sufficiently large capacitance is present and that saturations do occur.

The voltage changes resulting from the saturating process may be readily visualized with the aid of Fig. 8. The dashed line curves in this figure will be recognized as the three normal line-to-neutral transformer voltages. Assume the switch to be closed at t_0 and that due to the initial conditions the transformer of phase 2 saturates at time t_1. In accordance with the preceding discussion, the saturation of phase 2 will result in an abrupt rise in the capacitance or neutral voltage. For the purpose of illustration this rise may be assumed as vertical. After the single saturation is completed, the

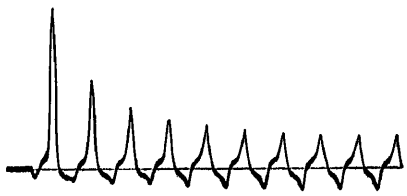

FIG. 7—TRANSFORMER STARTING CURRENT

high impedance of the transformers prevents the capacitance from discharging and the neutral voltage remains constant for the time being. However, the voltage which the capacitance has acquired adds to the voltage of phase 1 to result in an abnormally large voltage across its transformer. The large voltage, which in the figure is about twice normal, will saturate transformer No. 1 at about t_2. The second saturation is in the opposite direction to the first and consequently results in a reversal of the neutral voltage.

In case it is not clear that the second saturation occurring at t_2 would reverse the capacitor voltage, reference is made to the hysteresis loop of Fig. 10. Once a saturation starts, it will increase in intensity

until the transformer voltage reaches zero; for as long as there is some voltage, the flux continues to increase. After the flux reaches a maximum, at the instant the transformer voltage reaches zero, it must decline to its residual value. This partial collapse of the magnetic field induces a transformer voltage in the opposite direction. Consequently in Fig. 8, whenever a saturation is assumed to occur, the affected transformer voltage should be reversed by an appreciable amount

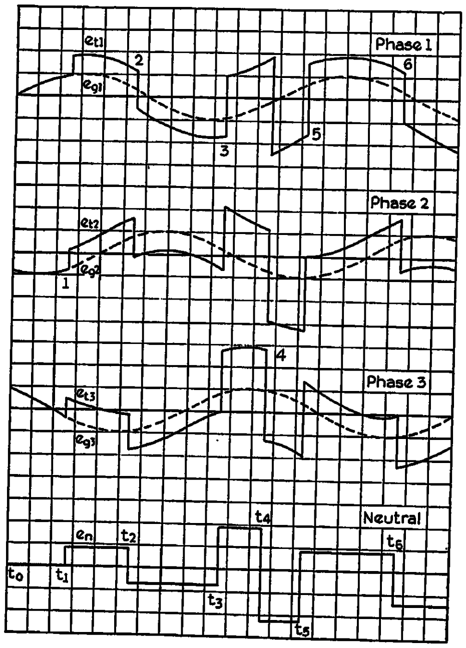

FIG. 8—HYPOTHETICAL VOLTAGES RESULTING FROM AN ARBITRARY SUCCESSION OF SATURATIONS

$$e_t = e_n + e_g$$

and the neutral and other voltages determined accordingly by the relations in equations (1).

The neutral voltage acquired at t_2 remains constant as before, while the transformers operate in the range of normal densities. Again the neutral voltage results in an abnormally large voltage across the transformer of phase 1 and it will probably saturate at t_3 in the opposite direction. This saturation reverses the neutral voltage a third time and the process may be continued for the fourth, fifth, and sixth saturations and so on indefinitely.

In essentials, Fig. 8 illustrates the origin of the abnormal voltages of this discussion, although the actual wave shapes obtained are not rectilinear. It is evident that the frequency of the voltages is dependent only upon the rate at which the saturations occur and it is not surprising that unusual frequencies have been observed. At the start when there are wide differences between the core conditions of the three transformers, the saturations occur in a more or less hit or miss fashion and the resulting neutral voltages are highly irregular. As the initial differences in core conditions begin to be smoothed out, the time of saturation becomes more and more dependent upon how the neutral voltages combine with the supply voltages. In order for the voltages to reach a sustained condition it is necessary that some sort of stabilizing process be present which will maintain the voltages within a stable zone. This requirement is satisfied by the formation of multiple saturations or the saturation of two or more transformers in parallel and in the same direction.* The proper stabilizing multiple saturations only occur for a limited number of neutral voltage frequencies, namely, one-half of, equal to, double, and triple the supply voltage frequency. Consequently these are the only frequencies which can become stable and reach the sustained condition.

In accordance with the preceding discussion the abnormal voltages may be said to be self-excited by successive alternate saturations and limited in magnitude and frequency by multiple saturations. The complete theory based upon these two principles explains in an adequate manner the observed characteristics of the phenomena.

THE CHARACTERISTICS OF A SINGLE SATURATION

From the preceding discussion it is evident that the phenomena originate as a result of a succession of individual saturations. It is desirable, therefore, to investigate in detail just what happens in Fig. 6A when a transformer saturates. The wave shape and magnitude of the resulting neutral voltages are of major importance.

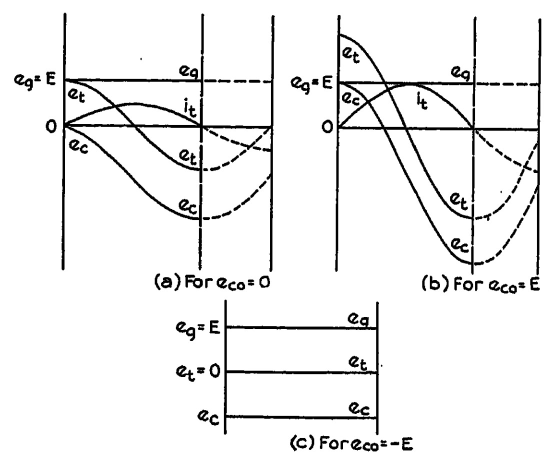

FIG. 9—STARTING VOLTAGES—CONSTANT INDUCTANCE AND CAPACITANCE IN SERIES

$$e_t = e_g + e_c$$

Wave Shape of the Neutral Voltage. Changes in the voltage across a capacitor in any circuit are dependent upon current and the time during which the current flows. The capacitances associated with the abnormal voltages in Fig. 6A are relatively large and require considerable currents to alter their charge in time inter-

*Direction of saturation as used here has a very definite meaning when referred to either Fig. 1A or Fig. 6A. Two or more saturations are in the same direction when their respective currents flow in the same direction at the neutral, that is, either out or in.

vals of the same order as the period of the supply voltage. At low densities the transformers possess high inductance, and the resulting small currents are insufficient to alter appreciably the charge upon the capacitor over considerable intervals of time. For that reason the normal operation of the transformers at low densities produces no appreciable effect upon the capacitor voltage. On the other hand, at high densities the inductance decreases to a small fraction of its normal value while the currents are often hundreds of times greater. Consequently, in deriving the effect of saturation in a single transformer the effect of

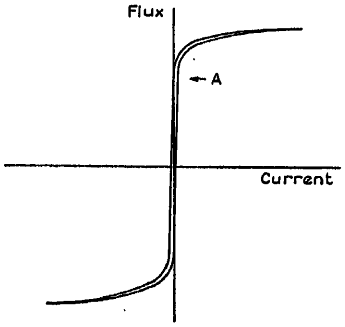

FIG. 10—HYSTERESIS LOOP

the two unsaturated transformers may be neglected. For such a case it is only necessary to consider a single phase portion of Fig. 6A such as is shown in Fig. 6B.

Fig. 6B is a relatively simple circuit and no particular difficulty is encountered in deriving the fundamental nature of the changes which occur even though the inductance may be variable. However, in order to connect the phenomena with more familiar circuits, assume first that the inductance is constant and apply a unidirectional voltage to the circuit. The resulting voltages and currents will oscillate as shown in Fig. 9a. The damping due to resistance may be neglected since the first half cycle or so is of sole interest here. In Fig. 9b curves are shown of voltages and currents for an initial capacitor voltage in one direction, and in Fig. 9c for an initial capacitor voltage in the other direction. In both of the latter figures, the initial capacitor voltage is equal in magnitude to the applied voltage.

The same surges of energy occur for a transformer and capacitance in series as for a constant inductance and capacitance in series. The wave forms of the resulting currents and voltages are different for the two cases due to the hysteresis loop relation between the transformer current and flux. However, just as constant inductances produce characteristic curves, namely, sine curves, due to the linear relation between current and flux, so also do iron core inductances produce characteristic curves as a result of the hysteresis loop relation between current and flux. Once established, the iron core inductance curves may be readily identified. In this manner voltage variations in an iron core inductive circuit can be described by reference to characteristic curves which are just as definite as the familiar hysteresis loop. Such curves are established in Figs. 11 and 12 which are the iron core inductance or transformer curves, from the circuit of Fig. 6B, corresponding to the constant inductance curves, Figs. 9a and b. Figs. 11 and 12 are based upon computations for transformers and capacitance approximating those used in some of the tests described by C. T. Weller.[5] The chief characteristics of these curves are explained on the basis of the hysteresis loop of Fig. 10. The curves were started at the point A on the loop in order to reach saturation more quickly. The small currents associated with the initial flux produce a negligible change in the capacitor voltage at first. However, the flux soon rises along the knee of the curve and the currents become abruptly larger resulting in an abrupt rise of the capacitor voltage. The flux continues to rise until the transformer voltage reaches zero. At this point there is no voltage tending to maintain the high currents in the transformer which are associated with the peak flux so that the magnetic field tends to collapse. The partial collapse of the magnetic field induces a reversed transformer voltage which may carry the capacitor voltage to a value far in excess of the applied voltage. Especially is this true when the proper initial capacitor voltage is present as in Fig. 12. The decay in the magnetic field continues until the current reaches zero. The density is now restored to a region of high permeability and consequently the transformer possesses a high inductance. The currents which then flow have very little effect upon the capacitor voltage so that it tends to be maintained at the value acquired during saturation.

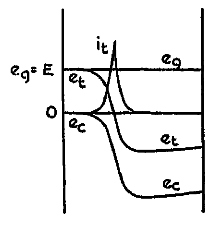

FIG. 11—SATURATION VOLTAGES FOR $e_{co} = 0$

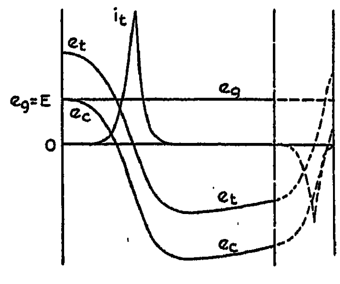

FIG. 12—SATURATION VOLTAGES FOR $e_{co} = E$

The negative transformer voltage in Fig. 12 resulting from the first saturation is maintained by the continued decay in flux through zero and down along the negative portion of the hysteresis loop. Eventually saturation in the negative direction will occur and the cycle of events is repeated as illustrated by the dashed line continuation of the curves. Although Figs. 11 and 12 have been derived with unidirectional applied voltage, their characteristic shape is also applicable to alternating applied voltage, since the transformer passes through the complete cycle of saturation and is restored to low density in a short time relative to variations in the applied voltage. In other words the alternating supply volt-

age would not vary appreciably while the phenomena occurs and may therefore be considered as unidirectional. The application of the characteristic curves to alternating supply voltages is shown in Fig. 14.

The abnormal voltages of this discussion are the result of a succession of alternate saturations each occurring in the manner just described. The remarkable similarity between the actual neutral voltage curve of Fig. 13 as obtained in the field and the computed curves of Figs. 11 and 12 is almost conclusive proof of the preceding statement. However, this close similarity is

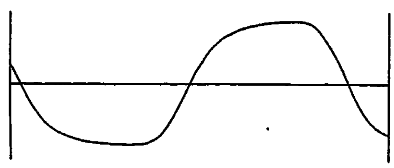

FIG. 13—FUNDAMENTAL FREQUENCY NEUTRAL VOLTAGE CURVE

not usually present although the neutral voltages practically always show the chief characteristics of the derived curves, namely, an abrupt reversal and rise of voltage followed by a slow droop toward zero. These characteristics are present in most of the neutral voltages of Figs. 2, 3, 4, and 5. The other variations present give insight into the processes whereby the voltages become regular and sustained as discussed in the following sections.

The Magnitude of the Neutral Voltage. Heretofore the discussion has proceeded upon the assumption that each saturation results in a reversal of the neutral voltage. Such is not always the case. It is true that the large voltage changes are the result of saturations which reverse the neutral voltages but it is also possible for minor saturations of small intensity to occur. Each minor saturation changes the neutral voltage by a slight amount and results in the irregularities which may be observed in the curves of Figs. 2 and 3. If it were not for their occurrence these neutral voltages would appear much more like those derived in Figs. 11 and 12.

The conditions which determine the intensity of a saturation and the magnitude of the neutral voltage resulting from it may be found from the instantaneous energy relations in the circuit. The various stages through which the voltages and currents pass during the saturation of a single transformer are investigated in detail in the Appendix. As a result of the deductions derived there, it has been possible to set up quantitative relations between the initial voltages and the final capacitor voltage. The final capacitor voltage has been found to depend upon its initial value just before saturation, the magnitude and direction of the supply voltage and the peak flux density which is reached. These factors are related as follows:

$$e_{cf} \mid e_{cf} \mid = - e_{go} \mid e_{go} \mid - P_w \{ e_{co} \mid e_{co} \mid + e_{go} \mid e_{go} \mid \} \tag{28}$$

Where:

e_{cf} = the final capacitor voltage.

e_{go} = the supply voltage at the instant the transformer voltage crosses zero.

e_{co} = the initial capacitor voltage just before saturation.

P_w = the ratio of the energy released to the energy stored in the transformer core during saturation.

The vertical bars enclose absolute values of the voltages. It is necessary to write the products in this form instead of as squares of the algebraic symbols in order to retain the proper signs. Had the terms been squared all of the signs would have been positive and, therefore, not generally valid.

In general the factors entering the relation may vary throughout a rather wide range. The only definite result of saturation in a single transformer is that the voltage across the saturated transformer must reach zero. Whether the capacitor voltage reverses or not depends upon the magnitude and direction of the supply voltage at that instant. The relation expressed in Equation (28) covers all possible cases. However, when the capacitor voltage is merely reduced in magnitude and not reversed by the saturation of a single transformer, the bias voltage is still maintained so that one of the other transformers will saturate later in the same direction and accomplish the reversal. In some cases as many as four single saturations occur in the same direction before the capacitor voltage reaches its maximum reversed value. The general term *saturation* as used here includes the complete group of single transformer saturations occurring in one direction at a given time. Although the minor saturations are more or less incidental and do not directly result in major

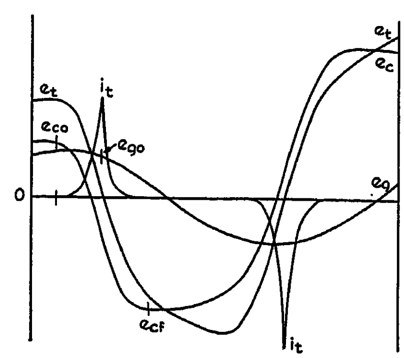

FIG. 14—TWO ALTERNATE SATURATIONS—A-C. SUPPLY

$e_t = e_g + e_c$

voltage fluctuations they function to stabilize the voltages in the sustained condition as explained below.

MULTIPLE SATURATIONS AND SUSTAINED VOLTAGES

Voltage Limitation and Stability. If the neutral voltages arising from a succession of alternate saturations are to become stable at a particular value, some process must be present to maintain and limit the voltages within the stable range. This process is found to exist as a result of multiple saturations. As ex-

plained before, a complete saturation resulting in a reversal of the neutral voltage may involve one or more transformers. Each single transformer saturation contributed a definite part of the total energy change. Multiple saturation refers to the condition where at least two such single transformer saturations occur in the same direction* to accomplish the neutral voltage reversal.

In general each succeeding major and alternate saturation tends to build up the alternating capacitor voltage just as indicated by Fig. 14 and by the transition from Fig. 11 to Fig. 12. As a matter of fact it has already been indicated that all sorts of saturations occur, resulting in voltage changes of from a slight reduction to a complete reversal. But the major saturations are the result of abnormally large transformer voltages which only occur when the neutral and supply voltages are in the same direction and add directly. This is the condition which produces the

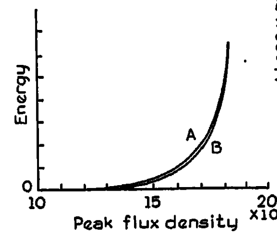

FIG. 15—MAGNETIC ENERGY OF OUR $C\ m^3$ TRANSFORMER STEEL

A. Stored or absorbed
B. Released

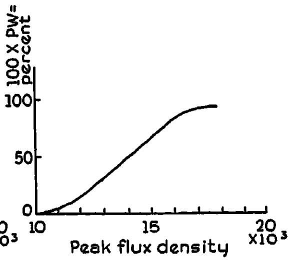

FIG. 16—RELEASED ENERGY IN PER CENT OF STORED ENERGY

largest reversed voltage and, therefore, the largest build up effect. As the voltages continue to rise, other transformers begin to reach saturation densities in the same direction. If the saturations fall into the proper phase with respect to the line-to-neutral supply voltages, a position will be reached in which a minor saturation occurs just before the main saturation. Such a condition is illustrated in Fig. 18 where the saturation of transformer 1 precedes the main saturation occurring in transformer 2. In accordance with the quantitative relations discussed in the preceding section and in the Appendix, the preliminary saturation of transformer 1 will reduce the initial voltage for the main saturation which in turn reduces the magnitude of the resulting reversed voltage. Thus when these preliminary saturations start to occur, the neutral voltages soon reach a limiting value where the preliminary saturation reduces the voltage by the amount of the build up effect. When each saturation occurs as a multiple saturation in this manner the condition is a stable one because a reduction of the neutral voltages, for any reason, makes the preliminary saturations disappear and the succeeding saturations will again tend to build up the voltages. On the other hand, if the voltages increase above the stable value the preliminary saturations will become more pronounced and cause their reduction.

This process is plainly evident in the neutral voltage curve of Fig. 3. Here a preliminary saturation reduces the voltage to a fairly small value, after which the main saturation occurs and results in the voltage reversal. In the case of Fig. 2 the reduction occurs in several steps as three or four saturations occur in

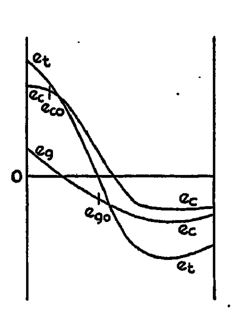

FIG. 17—SATURATION—REDUCTION OF REVERSED VOLTAGE

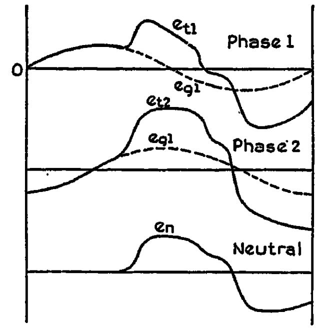

FIG. 18—DOUBLE SATURATION

multiple for each voltage reversal. All of the abnormal voltages observed possess these multiple saturations after they reach the stable state. Their effect is not always evident in the voltage curves since under certain circuit conditions the auxiliary stabilizing saturations occur too close to the main saturation and the effect of the first or stabilizing saturation merges into the effect of the second. This is the case in Fig. 13. The small auxiliary saturations are always evident in the current oscillograms, however, as shown in Figs. 19 and 20.

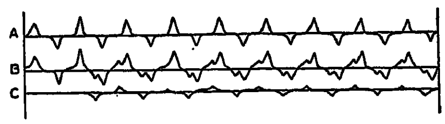

FIG. 19—FUNDAMENTAL FREQUENCY NEUTRAL VOLTAGE PHENOMENON (*C. D.* 120409 *B*)

Curve *A*—Transformer current phase 1
Curve *B*—Neutral current
Curve *C*—Transformer current phase 2

In general, therefore, the abnormal voltages tend to be cumulative but reach a limiting value when they give rise to the auxiliary stabilizing saturations just described.

Possible Sustained Neutral Voltage Frequencies. As a result of the stabilizing process the successive alternate saturations can only occur in the sustained condition at those frequencies which give rise to the proper stabilizing saturations. It should be emphasized, however, that the fundamental process involved in the generation of these voltages does not possess a definite

*Loc cit.

frequency characteristic. The saturations and resulting voltage reversals occur whenever the transformers reach saturation densities, and the neutral voltage frequency is dependent solely upon their rate. Consequently it is not to be expected that the possible sustained frequencies will necessarily be familiar multiples of the supply voltage frequency. In Figs. 21 to 26 the flux curves which result from the normal line-to-neutral voltage components are combined with the flux components resulting from various trial frequency

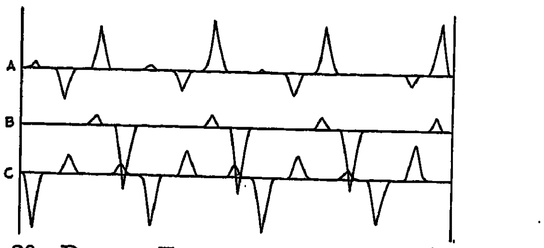

FIG. 20—DOUBLE FREQUENCY NEUTRAL VOLTAGE PHENOMENON (*C. D.* 120394)

Curve *A*—Transformer current phase 1
Curve *B*—Transformer current phase 2
Curve *C*—Transformer current phase 3 reversed with respect to *A* and *B*

neutral voltages in order to determine which possess the proper stabilizing conditions. The necessary conditions for a minor saturation to be effective in stabilizing the voltage are that it must precede the main saturation and that it will increase in importance as the neutral voltage increases, and decrease in importance as the neutral voltage decreases. An increase in neutral voltage causes an earlier rise in the flux curve so that these conditions are not difficult to recognize. Although sine curves have been used in these trials the flux curves resulting from the actual voltages are not materially different. The possible stabilizing saturations are numbered in the order of their occurrence except in Fig. 21, where there can be no doubt of their presence.

In each case illustrated by Figs. 21 to 26 some possible stabilizing saturations are present. In Fig. 23 both of those indicated occur on the same side of the cycle. Since the limitation must affect both halves of the wave such a condition is hardly stable. In Fig. 24 only two stabilizing saturations occur for the two cycles of neutral voltage. As one is positive and the other negative, stability is possible even though two peaks out of four are not affected. The conditions surrounding the actual formation of the double frequency voltages are rather critical. This fact fits in with the lack of complete stabilizing saturations. In Fig. 25 the stabilizing saturations continually diminish in magnitude, and the resulting voltages would be forced up to the next higher frequency. The six saturations per cycle illustrated by Fig. 26 have complete stabilizing saturations and should result in very stable voltages.

More than six saturations per cycle would require at least one transformer to saturate twice in the same direction for one half cycle. For uniform neutral voltages this is impossible. The second of the two required saturations would always occur too early and at a lower voltage than the first.

An inspection of Figs. 21 and 22 and the preceding discussion show that only 1, 2, 4, and 6 saturations per cycle possess the proper stabilizing saturations. Trials with other frequencies than those of Figs. 21 to 26, give strong indication that these include the only possible conditions although an infinite number of trials could be made. It is safe to conclude, therefore, that the frequency of the sustained neutral voltages obtained as the result of a stable succession of alternate saturations must be either one-half, equal to, double, or triple the supply frequency, since each complete saturation represents one reversal of the voltage.

In connection with the triple frequency voltages, it is necessary to distinguish here between what is ordinarily known as third harmonic intensification and triple frequency voltages which are excited by successive alternate saturations in accordance with the principles established above. Actually the transition in passing from one to the other is not very definite. However, third harmonic intensification is generally interpreted to mean that the capacitance current amplifies the normal third harmonics which already exist in the transformer voltages. In the case of third harmonic excitation by saturation it is entirely possible for the normal third harmonic voltages to be short circuited by the capacitance as has actually been observed.[5] With the proper conditions a closing of the switch in the same

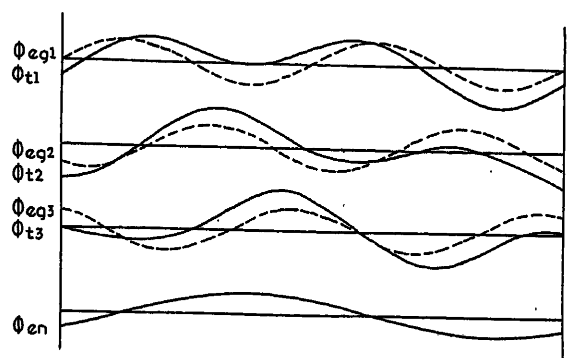

FIG. 21—ONE SATURATION PER CYCLE—MULTIPLE STABILIZING PEAKS

ϕ_t = total flux
ϕ_{eg} = supply voltage flux component
ϕ_{en} = neutral voltage flux component

circuit may give rise to abnormal triple frequency voltages which are self excited by saturation. In the case of third harmonic intensification the sustained voltages would occur as sustained phenomena after every switch closing, while in the case of triple frequency voltages from saturation they may occur only occasionally. As a matter of fact the terms used give sufficient distinction. Third harmonic intensification indicates an increase in third harmonic voltages which already exist, whereas the self excitation of third

harmonics by successive alternate saturations indicates that they need not necessarily be present in normal operation but may occur at times as a result of an abnormal condition, namely, transformer saturation.

Low Frequency Beats. With respect to the positive and negative flux curves the phenomena may be classified according to whether the neutral voltages result in symmetrical or unsymmetrical flux densities within the transformers. Figs. 21, 22, 24, and 26 permit the identification of each of the frequency conditions according to this classification. The one and four saturations per cycle phenomena obviously produce unsymmetrical densities. In three-phase circuits a certain degree of instability is an inherent accompaniment of the unsymmetrical densities and results in the low frequency variations in the flux densities and currents of the transformers which have been described.[1,4,5,6]

The instability occurs in the mean neutral voltage. For symmetrical densities a displacement of the mean neutral voltage increases the transformer losses in a way for which no energy is available and symmetry is

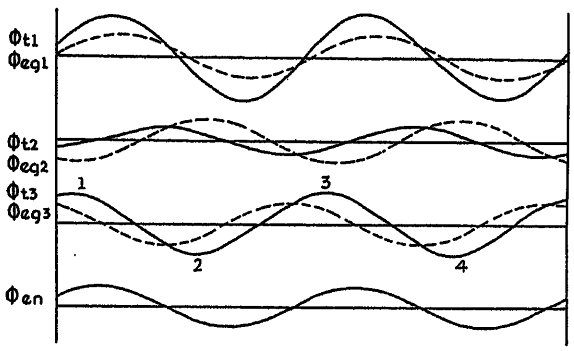

FIG. 22—TWO SATURATIONS PER CYCLE—STABILIZING PEAKS NUMBERED IN THE ORDER OF OCCURRENCE

restored just as the displaced single-phase transformer starting currents become symmetrical after a time. On the other hand the one-half and double frequency phenomena result directly in unsymmetrical densities so that the means exist inherently for their maintenance. The unsymmetrical densities, however, tend toward unequal positive and negative neutral currents since the shape of the magnetization curve precludes the possibility of the transformers operating at widely different densities and at the same time result in equal currents. The excess current occurring in a particular direction builds up a mean voltage on the capacitor of Fig. 6A. This voltage continues to rise until it builds up the flux density of the transformers to result in equal currents. The mean voltage then stops rising but the flux density resulting from it keeps on increasing. Unequal currents in the opposite direction result, which reduce and reverse the mean capacitor voltage until the process is repeated on the other side of zero. The continual surging between the mean capacitor voltage and the average density of all the transformers considered together gives rise to the beat phenomena. The beat phenomena are, therefore, inherent characteristics of the one-half and double frequency phenomena in the three-phase transformer circuit. The densities associated with both frequency conditions are sufficiently high to set up audible stresses within the transformers. The variation in the magnitude of the stresses produces the audible beats.

As a result of the beats the voltages due to the satura-

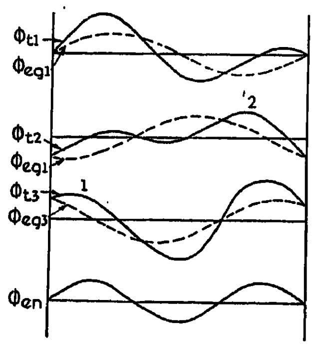

FIG. 23—THREE SATURATIONS PER CYCLE

Stabilizing peaks numbered in order of occurrence

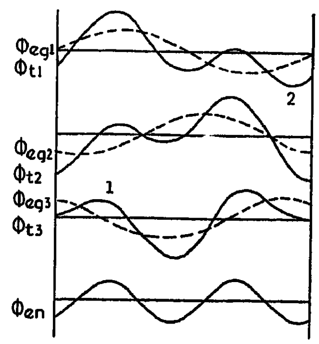

FIG. 24—FOUR SATURATIONS PER CYCLE

Stabilizing peaks numbered in order of occurrence

tions never occur at the exact rate of one-half or double the supply voltage frequency but differ therefrom by a small amount.

SOME APPLICATIONS OF THE THEORY TO THE OBSERVED VOLTAGES

Perhaps the most abundant proof of the foregoing explanation or theory of the abnormal voltages is afforded by a study of the irregular transients which

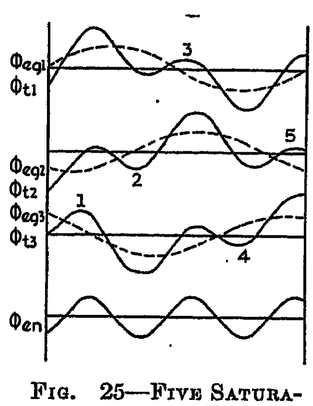

FIG. 25—FIVE SATURATIONS PER CYCLE

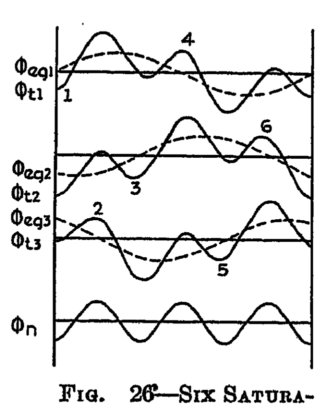

FIG. 26—SIX SATURATIONS PER CYCLE

have been recorded. These voltages are so irregular in magnitude and so indefinite in period that they must arise from such a chance process as the occurrence of successive saturations. The transients are important because they occur in every Y-connected transformer circuit. When delta-connected windings short circuit the neutral voltages they are of course suppressed in magnitude but the saturations still occur at the start

and the resulting circulating currents in the delta produce neutral voltages equal to their impedance drop. Also there must be quite a few Y-connected transformer circuits, of the type considered here, in which the system capacitances are not of the proper value to result in sustained voltages. Such circuits are subjected to abnormal voltages which go unnoticed due to their transient nature, but which may result in insulation failure.

On the other hand from the standpoint of instrument transformer operation as well as from the purely theoretical viewpoint, the sustained voltages are of greatest interest. Most of the available data apply to these phenomena.

Neutral Voltage Frequencies and Circuit Constants. Most any transformer operated at the usual core densities will saturate at least occasionally just after starting. For a given transformer bank the occurrence of a particular frequency phenomenon is dependent upon the starting conditions and upon the capacitance of the circuit. The higher values of capacitance are associated with the lower frequency neutral voltages and each frequency condition has a range of capacitance within which the phenomenon occurs. The ranges for the different frequencies overlap so that a given value of capacitance may result in either one of two frequency conditions, depending upon which of the two corresponding stabilizing conditions the voltages happen to fall into during the transient state.

For a particular system or value of capacitance the larger transformers are associated with the higher frequencies, assuming that they operate on the same voltage. A general relation between the transformer size and capacitance can be arrived at from the standpoint of energy. The larger transformers have greater amounts of energy stored in the transformer core and consequently require a larger capacitor, for the same frequency of saturation, to absorb the energy.

The Neutral Voltage and the Supply Voltages. The stabilizing process depends upon the neutral voltages building up until they result in the formation of the stabilizing saturations which occur when a certain value of flux density is reached. The peak flux is, therefore, roughly fixed by the relations existing between the stabilizing and main saturations. For a given frequency phenomena in a particular circuit these relations are approximately constant so that limitation occurs at a roughly constant peak flux. These relations can be expressed best in mathematical form. If ϕ_p represents the value of peak flux at which stabilization occurs and ϕ_g represents the normal peak flux the neutral of capacitor voltage may be thought of as due to the variation in the difference between these two flux values. Thus

$$\phi_c = \phi_p - \phi_g \qquad (2)$$

and the r. m. s. neutral voltage may be roughly expressed as

$$E_c = k\, f_c\, \phi_c \qquad (3)$$

For a given frequency, f_c, as the supply voltage increases, *i. e.*, if ϕ_g increases, ϕ_c and E_c must decrease. Thus over the range of supply voltage for which a particular phenomenon is sustained, the neutral voltage will tend to vary in an inverse relation to the supply voltage. This fact is excellently illustrated by the data in Table IV of the companion paper by A. Boyajian and O. P. McCarty[6] and also in some of the tabulations of C. T. Weller.[5]

For neutral voltages of the same as system frequency C. T. Weller has pointed out that the neutral lies sometimes within and sometimes outside of the delta voltage triangle. In the first case the neutral voltage is not quite sufficient to offset the normal line-to-neutral voltage and the neutral lies inside. In the second case the neutral voltage is greater than the normal line-to-neutral voltages and the neutral lies outside the delta voltage triangle. In accordance with Equations (1) and (2) the mere raising of the supply voltage will reduce the neutral voltage and bring the neutral inside the triangle. Thus the neutral lies inside when the supply voltage is relatively high, and outside when the supply voltage is relatively low. This variation is illustrated in Table II of C. T. Weller's paper where 94 per cent excitation results in a neutral just outside the triangle, whereas 104 per cent brings it well inside.

Relation between the Neutral Voltage and Its Frequency. From Equation (4) it may be deduced that for a given bank of transformers the neutral voltages will increase in the same order as their frequency. That this is true is also clearly illustrated in Table II of Weller's paper where phenomena *C*, *A*, and *B* represent the one-half, equal to, and double system frequency voltages respectively.

Equation (4) cannot always be applied so successfully to phenomena of different frequencies, due to the variation in the peak densities, or ϕ_p, at which the stabilizing saturations form. In general ϕ_p will be much lower for the equal to system frequency phenomenon than for either the one-half or double frequency phenomena.

Characteristics of Voltages Having System Frequency. In the two companion papers this phenomenon is termed neutral shift or phenomenon *A*. In both papers the voltages are represented by a conventional vector diagram.

The successive saturation theory of these voltages requires that the neutral voltage curve fall between the voltage curves of the transformers giving the main and stabilizing saturations. As a result the neutral voltage must always be about opposite to the third transformer voltage which lies half way between the two other voltages. This relation is illustrated in Fig. 22. The neutral, consequently, always falls in the general direction of one apex of the delta voltage triangle in a vector diagram.

As discussed elsewhere, variations in capacitance vary the phase of the neutral voltages so that the phase

relations are not always exactly the same. However, the preliminary saturation tends to be smaller and must occur in the transformer occupying the leading phase with respect to the main saturating transformer. Since the transformer in the leading phase thereby operates at a slightly lower density, its voltage should ordinarily be slightly lower than that of the main saturating transformer. In connection with the data on phenomenon A in Tables II and III (C. T. Weller[5]) it will be noted that the smaller of the two large voltages does occur in the transformer occupying the leading phase.

The Phase of the Stabilizing Saturations as Dependent Upon Capacitance. Within the range of capacitance which will sustain a given frequency a decrease in capacitance results in a more rapid rise of the neutral voltage. This causes the stabilizing saturations to occur earlier or in other words lengthens the time interval between the stabilizing and main saturations. It is to be concluded that the neutral voltages of Fig. 3 were obtained with relatively small capacitances whereas the neutral voltages of Fig. 13 were obtained with a relatively large capacitance. In the first case there is an appreciable interval between the stabilizing and main saturations; in the second, the two practically coincide.

Peak Flux Density and Capacitance. In accordance with the relations derived in the Appendix, the peak flux density during saturation tends to increase with increase in capacitance. It is to be expected in general, therefore, that as the capacitance is increased the neutral voltage would show some increase although not in proportion to the capacitance due to the relations involved in equations (3) and (4). This variation is illustrated by Table IV of the companion paper by Boyajian and McCarty.

Relation of Beat Frequency to Capacitance and Supply Voltage. The increase in flux density accompanying the rise in capacitance increases the asymmetries of the currents in cases of one-half and double frequency neutral voltages. The variations of the mean neutral voltage therefore occur at an increased rate since the excess currents are accumulated faster. This variation of the beat frequency with capacitance is illustrated by Table III of the companion paper by Boyajian and McCarty. Also illustrated in that table is the increase in beat frequency with decrease in supply voltage. The decrease in supply voltage causes larger neutral voltages, also giving rise to greater asymmetry in the currents and consequently more rapid beats.

Basis for Predicting the Occurrence of Any Given Phenomena. A complete discussion of this subject obviously includes a large number of detailed considerations. A basis for considering any particular set of transformers rests in the stabilizing process. This depends upon the flux density reaching a given value, namely, that at which the stabilizing saturations occur. Thus regardless of the size of core, number of turns, etc., for a given frequency of successive saturations the flux-density-time curves must have a fairly definite shape. With this as a basis the occurrence of a particular frequency neutral voltage can be predicted from the total capacitance and the transformer structure specifications.

Capacitance within the transformer must be included in determining the total capacitance. To maintain a given phenomenon with a particular size of core and a variable number of turns, the total capacitance must vary inversely as the square of the turns. However, the capacitance between layers and turns of a winding increases as the first or higher power of the turns so that as the turns are increased a point is reached where further increase offsets any decrease which may be possible in the external capacitance. This may be the reason why all investigators have not been able to duplicate the double and triple frequency phenomena in the laboratory. For the higher frequencies the number of turns should be low in comparison with the size of core. In general this would mean transformers with a fair load capacity instead of small potential transformers and the like.

Prevention of the Phenomena. The circuit considerations indicate that the phenomena may be prevented by decreasing the capacitance to well below that necessary to sustain the triple frequency phenomena or to increase it to well above the limit for sustaining the one-half frequency phenomena. The wide range of capacitance within which the phenomena are sustained makes this procedure of doubtful practical value in most cases.

The phenomena may be damped out with transformer line-to-neutral loading sufficient to dissipate, in one-half cycle of neutral voltage, the energy acquired by the capacitor from the supply voltage during the previous saturation.

CONCLUSIONS

It is to be concluded that the abnormal line-to-neutral voltages which have been observed at various times in the field and laboratory are the direct result of a succession of saturations in the transformer cores.

In the transient state the initial asymmetries of the core flux densities result in saturations of a highly irregular order and produce correspondingly irregular voltages having no definite frequency. The abnormal voltages are sometimes limited within a stable zone as a result of multiple saturations and thereby become sustained. The stabilizing process only occurs for neutral voltage frequencies of either one-half, equal to, double, or triple the supply voltage frequency; consequently, these are the only frequencies which can exist in the sustained condition.

The successive saturations giving rise to the abnormal voltages do not possess a definite frequency characteristic, and as a result frequencies occur which are not ordinarily expected in ordinary alternating current circuits.

The minor and incidental characteristics of the published data bear a definite relation to the process of

successive saturations and are adequately explained by this theory.

Appendix

Proof for the Equivalent Circuit. Mathematical analysis has a limited use in the treatment of iron-clad circuits. In this discussion, however, its application enables the substitution of a more simple circuit than that actually found in practise. All of the relations established in the following analysis involve instantaneous values only and thereby apply to all wave shapes.

The circuit of Fig. 1A comprises a Y-connected bank of transformers (with neutral grounded) connected to ungrounded three-phase delta voltages. The line-to-ground capacitance of lines, transformer bushings, switches, etc., are represented by the lumped capacitances C_1, C_2, and C_3. Since the ground only serves as the connection between the capacitors and the transformer neutral the connection may be made direct and each capacitance shunted across its transformer as in Fig. 1B. This circuit is quite complicated. A complete treatment would involve simultaneous consideration of six currents to say nothing of the transformer flux-current relations.

The three transformer voltages, however, may be resolved into three known components and one unknown, that is symmetrical components and components of zero phase sequence respectively. The three symmetrical components are so related that:

$$e_{a1} + e_{a2} + e_{a3} = 0. \tag{4}$$

For the zero phase sequence components the relation is:

$$e_{b1} = e_{b2} = e_{b3} = e_b \tag{5}$$

Each transformer voltage is the sum of its components, thus,

$$\left.\begin{aligned} e_{t1} &= e_{a1} + e_{b1} \\ e_{t2} &= e_{a2} + e_{b2} \\ e_{t3} &= e_{a3} + e_{b3} \end{aligned}\right\} \tag{6}$$

and from the definition of neutral voltages as given in an early part of the paper, namely:

$$\frac{e_{t1} + e_{t2} + e_{t3}}{3} = e_n \tag{7}$$

it is evident that

$$e_n = e_b$$

For normal operation of the transformers from balanced supply voltages the three transformer voltages add to zero, and, consequently, the neutral voltage is zero. For abnormal operation each transformer voltage consists of a symmetrical component plus the neutral voltage. The latter voltage component being common to each of the transformers.

In Fig. 1A the transformer voltages are functions of theirr espective currents. The three currents are so related that,

$$i_{t1} + i_{t2} + i_{t3} = i_n \tag{8}$$

The three capacitor currents are similarly related,

$$i_{c1} + i_{c2} + i_{c3} = - i_n \tag{9}$$

In terms of the transformer voltages the three capacitor currents are:

$$\begin{aligned} i_{c1} &= C_1 \frac{d\,e_1}{d\,t} = C_1 \left(\frac{d\,e_{a1}}{d\,t} + \frac{d\,e_n}{d\,t} \right) \\ i_{c2} &= C_2 \frac{d\,e_2}{d\,t} = C_2 \left(\frac{d\,e_{a2}}{d\,t} + \frac{d\,e_n}{d\,t} \right) \\ i_{c3} &= C_3 \frac{d\,e_3}{d\,t} = C_3 \left(\frac{d\,e_{a3}}{d\,t} + \frac{d\,e_n}{d\,t} \right) \end{aligned} \tag{10}$$

thus from equation (9):

$$- i_n = C_1 \frac{d\,e_{a1}}{d\,t} + C_2 \frac{d\,e_{a2}}{d\,t} + C_3 \frac{d\,e_{a3}}{d\,t} + (C_1 + C_2 + C_3) \frac{d\,e_n}{d\,t} \tag{11}$$

For the special case where

$$C_1 = C_2 = C_3 = C_0$$

the capacitance may be factored from the differential coefficients of the symmetrical components after which the latter will add to zero in accordance with the result of differentiating equation (4), so that,

$$i_n = - 3\, C_o \frac{d\,e_n}{d\,t} \tag{12}$$

In other words the neutral current, for balanced line-to-neutral capacitance, is dependent upon the total capacitance and the neutral voltage. It is independent of the voltage-current relations within the transformers except indirectly as these alter the neutral voltage.

Any equivalent circuit will be satisfactory for balanced capacitance, provided the transformers retain the same connections and have the same neutral current as in the actual circuit. Only the neutral current is dependent upon conditions external to the transformers.

That these conditions are satisfied by Fig. 6A may be readily demonstrated. Here a definite supply voltage is assumed in the form of a three-phase Y-connected generator. The three symmetrical line-to-neutral generator voltages are related by:

$$e_{g1} + e_{g2} + e_{g3} = 0 \tag{13}$$

Each of the three single-phase closed circuits comprise voltages so related that,

$$\left.\begin{aligned} e_{g1} &= e_{t1} + e_o \\ e_{g2} &= e_{t2} + e_o \\ e_{g3} &= e_{t3} + e_o \end{aligned}\right\} \tag{14}$$

From equations (6) and (13):

$$\frac{e_{t1} + e_{t2} + e_{t3}}{3} = - e_o = e_n \tag{15}$$

From which the neutral current becomes,

$$i_n = - C_n \frac{d\,e_n}{d\,t} \tag{16}$$

Therefore, in so far as the transformers are concerned the circuit of Fig. 6A is electrically identical to that of Fig. 1A provided:

$$C_1 = C_2 = C_3 = C_o \tag{17}$$

and

$$C_n = 3\,C_o \tag{18}$$

It is significant that these deductions are independent of anything which may go on within the transformers. In fact the lumping of the capacitances may be applied equally well to any type of Y-connected similar or dissimilar impedances which may be substituted for the transformers.

The total effect of unequal capacitances may be illustrated by assuming that C_1 is the smallest of the three capacitances. Equation (11) may be written for this case in the form

$$- i_n = (C_2 - C_1)\frac{d\,e_{a2}}{d\,t} + (C_3 - C_1)\frac{d\,e_{a3}}{d\,t} + (C_1 + C_2 + C_3)\frac{d\,e_n}{d\,t} \tag{19}$$

Thus the capacitance may still be lumped in so far as the current resulting from the neutral voltage is concerned. In addition, however, there are components of current equal to the products of the excess capacitances of two legs and the differential coefficients of their respective symmetrical component voltages. In other words, as long as the total capacitance remains the same, making the individual capacitances unequal will only result in additional neutral currents of the same frequency as the supply voltages. No change in the neutral voltage frequency currents will occur. For cases where e_n is large compared to e_a or where the capacitance unbalance is small the effect of the unbalance is negligible.

Energy and Voltage Relations During Saturation. The energy stored within a capacitor at any instant, is a function of the voltage at that instant, regardless of the variations which may have occurred previously. By means of this fact it is possible to derive quantitative expressions for the surges of energy between the capacitor and transformer during saturation without taking into consideration the time required for the completion of the process.

Let the sinusoidal supply voltage be represented by e_g in Fig. 14 which illustrates saturation voltage curves for the circuit of Fig. 6B. The three voltages of the circuit must maintain the relation

$$e_t = e_g + e_c \tag{20}$$

As indicated in Fig. 14 saturation starts at e_{co}. Its immediate effect is the reduction of the transformer voltage, e_t, to zero. This occurs at the point marked e_{go} where the capacitor voltage is equal and opposite to the supply voltage in accordance with equation (20). During the time e_t is reaching zero, e_c drops from e_{co} to zero and then rises to $- e_{go}$. The first step results in a loss of energy by the capacitor of

$$w_o = 1/2\,C\,e_{co}^2 \tag{21}$$

The second step results in an acquisition of energy by the capacitor of

$$w_1 = 1/2\,C\,e_{go}^2 \tag{22}$$

Thus the total change in energy of the capacitance is

$$w_{o1} = 1/2\,C\,(e_{co}^2 + e_{go}^2) \tag{23}$$

This energy change in the capacitor results in a corresponding rise of magnetic energy stored within the transformer core. The energy acquired by the core is a function of maximum flux density as shown by curve *A* of Fig. 15 which represents the energy of one cubic cm. of typical transformer steel. Consequently by means of equation (23) and curve *A* of Fig. 15 the peak flux density reached during any saturation may be computed for a given core volume. In this manner quantitative relations are available from the time saturation starts until the transformer voltage reaches zero. After the transformer voltage reaches zero the magnetic field collapses regardless of further variation in the supply voltage. A portion of the magnetic field energy is thereby returned to the capacitor and results in a further change of its voltage. The actual energy returned is given by curve *B* of Fig. 15. However, it is of considerable advantage to express this returned energy as a fraction of that acquired. This factor, P_w, is shown in Fig. 16. From equation (23) the energy returned in the collapse of the magnetic field is

$$1/2\,P_w\,C\,(e_{co}^2 + e_{go}^2) \tag{24}$$

As above described the complete change in the capacitor voltage from its initial to its final value occurs in three steps. First, the capacitor voltage reaches zero; second, it reaches a value equal and opposite the supply voltage at the instant the transformer voltage reaches zero; and third, the capacitor acquires the energy of the magnetic field and reaches its final value. The final energy stored within the capacitor may be written

$$1/2\,C\,e_{cf}^2 = 1/2\,C\,e_{go}^2 + 1/2\,P_w\,C\,(e_{co}^2 + e_{go}^2) \tag{25}$$

and the final voltage becomes

$$e_{cf}^2 = e_{go}^2 + P_w\,(e_{co}^2 + e_{go}^2) \tag{26}$$

The exponents in the energy equations eliminate the effect of signs so that other possibilities may occur which would not conform with equation (26). For instance, it frequently happens that the transformer voltage does not reach zero until after the supply voltage is reversed. The curves for such a condition are shown in Fig. 17. For this case the energy relations result in a final voltage such that

$$e_{cf}^2 = - e_{go}^2 + P_w\,(e_{co}^2 - e_{go}^2) \tag{27}$$

If a general relation is to be established, which will be applicable to all cases, the terms in the equation cannot be squared for in doing so they lose their signs. The difficulty may be avoided by the use of products of absolute and algebraic values. Such a product has the same magnitude as the square of the algebraic value but retains its original sign. The absolute values

may be represented by enclosing them between the usual vertical bars. The general relation written in this manner is:

$$e_{cf}\,|\,e_{cf}\,| = -\,e_{go}\,|\,e_{go}\,| - P_w\,\{e_{co}\,|\,e_{co}\,| + e_{go}\,|\,e_{go}\,|\,\} \tag{28}$$

In any case the significant result is that the final voltage of the capacitance is dependent upon the initial capacitor voltage at the start of saturation and upon the supply voltage at the instant the inductance voltage reaches zero. Where equation (26) applies, the initial capacitor voltage is often many times the supply voltage and therefore dominates in the expression for the final reversed voltage. However, due to the factor P_w the final reversed voltage cannot exceed the initial voltage without the energy contributed by the supply voltage. These equations, therefore, illustrate the specific manner by which the capacitor voltage may be maintained. In equation (27) if e_g is quite large the capacitor voltage may not be reversed at all but merely reduced in magnitude. This tendency, for such a case, is amplified by the smallness of P_w for, when the energy contributed to the core is not the result of the sum of e_c^2 and e_g^2 as in equation (26), the peak densities reached are usually low so that P_w is small in accordance with Fig. 16. Thus the capacitor voltage resulting from a saturation is largely dependent upon the point on the supply voltage cycle at which the saturation occurs. This characteristic is of major importance in establishing the conditions for a stable succession of alternate saturations.

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Discussion

EXPERIENCES WITH GROUNDED-NEUTRAL, Y-CONNECTED POTENTIAL TRANSFORMERS ON UNGROUNDED SYSTEMS

(WELLER)

PHYSICAL NATURE OF NEUTRAL INSTABILITY

(BOYAJIAN AND MCCARTY)

THEORY OF ABNORMAL LINE-TO-NEUTRAL TRANSFORMER VOLTAGES

(LAPIERRE)

J. Fallou: I believe that the two phenomena analyzed by Messrs. A. Boyajian and O. P. McCarty can find an immediate and common physical explanation if based on the following experimental data:

1. Fig. 1 is a circuit comprising an a-c. source of frequency f_o, an air-core inductance L, and a capacitance C. It is known that if the conditions of such a circuit are altered, there appears across the terminals of the inductance and the capacitance a voltage comprising; (a) a steady state term of frequency f_o; (b) a transient term of frequency f'.

$$f' = \frac{1}{2\,\pi\,\sqrt{C\,L}}$$

If it is desired to maintain at the terminals of the capacitance a voltage of frequency f', it is necessary and sufficient that the frequency f_o of the source, or one of its higher harmonics, be equal to the desired frequency f'. In particular, it will never be possible to obtain, in a permanent manner, a frequency lower than f_o.

Let the air-core winding be now replaced by one with a magnetic core, with a self-inductance L (as determined by the straight portion of its magnetization curve) the same as before. The closing of the switch produces, as before, a transient voltage across the terminals of the capacitor, the sum of a free and forced state. But it is possible that the intensity of the current produced by the free oscillation be far greater than that arising from the permanent term, in some cases sufficiently large to saturate the magnetic core. The voltage across the terminals of the capacitor then contains a fundamental wave f' accompanied by a series of harmonics. Generally, such a free oscillation dies out following a very complex law, and its wave shape also changes as the current decreases.

However, I have shown experimentally in 1926* that if the frequency of one of the harmonics of such a free oscillation is near that of the source, the entire free oscillation, including its fundamental component, may become sustained.

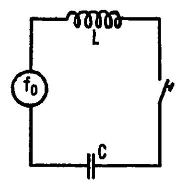

FIG. 1

Thus, a frequency lower than that of the applied e. m. f. may be found to persist across the terminals of the self-inductance or of the capacitance.

I have also found and described a static frequency reducer.† This apparatus operates on a principle totally different from that of frequency multipliers based on ferro-resonance used for a long time: it utilizes the maintenance of a free oscillation (which is necessary to start first) by one of its harmonics; while, in the frequency multipliers, on the contrary, a forced and distorted oscillation is produced, one of the harmonics being assumed as intensifying through an arrangement for resonance. Besides, frequency multipliers do not furnish even harmonics without the introduction of direct current into the circuit, while this arrangement furnishes directly an even multiple of the basic frequency.

2. Profiting by my experiences, Mr. E. Rouelle has been able to generalize the proposition which I have demonstrated; he has shown that in a circuit containing an iron-core inductance and a capacitance, fed by a sinusoidal e. m. f., it is possible to maintain various oscillations, the frequency of which can be not only even or odd sub-multiples of the source, as I have shown, but also even or odd multiples.

Thus, the following proposition is found definitely demonstrated:

In a circuit containing an iron-core winding and a capacitor, if a free non-sinusoidal oscillation of fundamental frequency f' is

*J. Fallou: *Revue Generale de l'Electricite* 1926—T. XIX, p. 987.
†American Patent No. 1,633,481.

started, such an oscillation can be maintained from a source of frequency f which is higher than, equal to, or lower than f', provided that f and f' have a simple ratio (even or odd, integral or fractional).

3. Finally, M. Rouelle has verified the following by test: Three iron-core windings $O\ A_1$, $O\ A_2$, and $O\ A_3$ (Fig. 2) have a common point O, and are connected respectively to three capacitors $A_1\ C$, and $A_2\ C$, and $A_3\ C$.

Excitation is applied between O and C from a source of frequency f; after which, on starting oscillations in one of the circuits, it is possible to maintain, across the terminals of $C\ A_1$, $C\ A_2$ and $C\ A_3$, three voltages at a frequency f' equal to one-third of f, each one of these voltages being spaced one-third of a cycle away from the adjacent circuit. M. Rouelle has thus shown the possibility of static transformation of a single-phase voltage of frequency f to a polyphase voltage of frequency f' sub-multiple of f.

It is clear that the last experiences of Rouelle demonstrates a phenomenon which is the reciprocal of that which happens in case of neutral oscillations.

As to the inversion of the neutral, it can be proven through the same mechanism, the sustained frequency f (oscillation of the neutral) is then almost equal to the sustaining frequency f'. The experiences of Messrs. Boyajian and McCarty have led the authors to sustain at the neutral point of the system oscillations at the frequency f equal to f' (inversion and oscillation at the frequency $f'/2$): by changing the test conditions, that is, the capacitances and the degree of the saturation of the iron, other frequencies could also have been put into evidence.

This explanation is otherwise very close to those given by Messrs. Boyajian and McCarty: it may not be without interest to state in passing, that these authors have been able to deduce

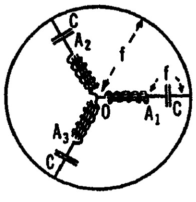

FIG. 2

a general law (maintenance of a harmonic or sub-harmonic), starting from a particular case (instability of neutral) while on our side, we have been led to traverse the same course in the reverse direction, M. Rouelle having explained the instability of the neutral starting from the law of maintenance which I demonstrated several years ago.

F. A. Hamilton, Jr.: The first of these papers outlines experiences with two applications of grounded-neutral potential transformers on portions of systems necessarily operated ungrounded at certain times. These two installations provide outstanding examples of the difficulties which may be encountered with such installations.

In addition to the two cases which are cited in the paper it may perhaps be interesting to call attention to several other similar cases.

A. A bank of grounded-neutral potential transformers was connected directly to the terminals of a bank of delta-connected power transformers. The potential transformer secondaries were connected in "broken delta", the circuit being closed through a potential relay. When the power and potential transformers were energized this relay operated and tripped the breaker. The difficulty in this case was obviated by the expedient of opening the relay trip circuit automatically just before closing the energizing breaker and closing the relay trip circuit automatically some time after the breaker was closed. The voltage which operated the relay when this automatic scheme was not used seemed to be a transient one which died out rather rapidly, making it possible to use the relay, which was provided for ground protection, at all times excepting when energizing the power transformer bank.

B. A case similar to that referred to under (A) was observed by the writer. In this case a delta-connected power transformer bank was arranged to be normally connected to a short section of bus by means of a breaker. A bank of grounded-neutral potential transformers was connected to the short section of bus. The potential transformer secondaries were connected in broken delta and the circuit closed through a potential relay. When the installation was first placed in operation, the closing of the breaker between the power transformer bank and the short section of bus invariably caused the operation of the relay in the secondary delta of the potential transformers. This difficulty was partially cured by the addition of a resistance burden to the secondaries of the potential transformers. As this method of curing the difficulty did not seem desirable to the operator, the potential relay was replaced by a lower resistance current relay and this cured the difficulty satisfactorily. As in the case discussed under (A), the unbalance voltage was a transient one which died out rather rapidly and which did not persist as in the cases described in the paper.

C. On another system employing distribution lines at generator voltage, the insulation on an oil circuit breaker broke down. Grounded neutral potential transformers with secondaries connected in broken delta, the circuit being closed through potential relays were used on this system. These should not have caused trouble as the generator neutral was normally grounded. Examination of the breaker which failed, and of others in the same station indicated the possible presence of overvoltages, and although no definite solution was ever arrived at, it is thought that at times the operator in the station may have left the generator ungrounded and that resulting abnormal voltages to ground may have been responsible for the disturbance.

D. On one other system tests were made to determine the effect of using grounded-neutral potential transformers on an ungrounded system. In this case the secondaries were also connected in broken delta and the circuit closed through potential relay. In this case, the neutral was shifted outside the delta of the system voltage and this unbalanced condition persisted. It was cured by adding a resistance burden to the secondaries of the potential transformers.

In the four cases mentioned above, one of the systems operated at 60 kv. one at 12 kv. and the others at about 13.8 kv.

The examples mentioned may serve to illustrate that the difficulty which may attend the use of grounded-neutral potential transformers on ungrounded systems or portions thereof, have been more frequent than might be believed.

John Auchincloss: While the most important, and probably the most frequent, use of Y-connected potential transformers occurs in connection with ground protective equipment operating on the zero phase sequence components of current and voltage there are nevertheless a few other aspects of the general problem of the Y-connection upon which the various phenomena disclosed by these papers may have a profound bearing. Quite apart from the hazard to the potential transformers themselves and all other equipment subjected to the stresses arising from the phenomena which they engender, there is the further question of the degree of confidence which may be placed in the indications of instruments or devices operating from the secondary L/N voltages of such potential transformers.

Two situations immediately come to mind in which the occurrence of the neutral phenomena described in the papers may give rise to very misleading or entirely false conclusions in attempting to interpret certain system conditions from the readings of instruments connected to Y-connected potential transformers. These involve the phase comparison of system voltages for purposes of synchronizing across grounded Y-delta power transformer banks, and the detection of accidental grounds

on isolated-neutral systems operating at voltages beyond the range of the ordinary electrostatic ground detector.

When it becomes necessary to synchronize across a Y-delta power transformer bank two parallel voltages, namely, the L/N voltage on the Y side and the L/L voltage on the delta side, are available for connection to the synchroscope, and if a Y-connected set of potential transformers on the Y-side is also available the prospect of using the L/N voltage on this side for purposes of phase comparison appears attractive by reason of its simplicity. The situation to which I have particular reference is that in which the paralleling breaker is located on the Y- or high-voltage side of the bank and a group of relaying potential transformers is present on the same side. Obviously the L/L voltages across the power bank are 30 deg. displaced at synchronism, requiring the use of phase-shifting auto-transformers, two-winding potential transformers or other special equipment to offset this displacement at the synchroscope. To avoid the added complication brought about by these auxiliary devices many engineers are prone to favor the L/N voltage on the Y-side with balanced Y burdens, for purposes of synchronizing. However, a little consideration will show that if the relaying potential transformers are to be used also for synchronizing they must be connected to the line side of the paralleling breaker which of course is also the side of the breaker away from the Y windings of the power bank carrying the ground. Consequently with the breaker open the potential transformers may or may not be connected to a temporarily ungrounded portion of the system, depending upon the switching arrangements and ground locations that may obtain for the time being on that part of the system to which the potential transformers are connected. Should these conditions be such that during the synchronizing period this part of the system is ungrounded, then obviously the potential transformers are operating under circumstances which these papers describe as ideal for the propagation of neutral phenomena, with its resultant distortion of the L/N voltages. Under conditions such as these the danger of misleading indications at the synchroscope is obvious, as is also the conclusion that although the practise of synchronizing on the L/N voltage may be condoned under certain favorable circumstances it should be rigorously shunned under conditions at all likely to give rise to vagaries in the position of the system neutral.

The other problem apparently involved with the phenomena described in the papers is that of detecting accidental grounds on high-voltage, normally ungrounded systems. Most methods so far devised for obtaining such indications have depended essentially upon the secondary Y voltages obtained from three potential transformers connected to the lines in Y formation, with the primary neutral point of the potential transformers solidly grounded. Since the system is ungrounded this situation also results in a set of conditions most favorable to the inception of the phenomena, with resulting erroneous indications on the voltmeters or other ground-detecting devices operating on the secondary voltages. Fortunately, however, and for several reasons, among them being the advantages accruing from the use of standard 110-volt indicating devices, the potential transformers so far used for this purpose have invariably been of a rating suitable for the L/L voltage. Although a number of these ground-detecting equipments have been in apparently successful operation for several years nevertheless since all of the papers indicate that instability may occur even down to 58 per cent of normal excitation it is not at all improbable that the accuracy so far obtained from them may be susceptible to improvement by the addition of suitable secondary loading.

W. Lampert: At frequencies, the ratio of which compared with the impressed frequency is *not* an integer, an alternating bias is necessary. But I do not think, that at even harmonics, the ratio of which *is* an integer of the fundamental frequency, a bias is at all necessary.

Take for instance the case, where there is no bias and no residual flux, and where in the leg voltage there is a fundamental and a second harmonic. Then a current of fundamental and double frequency will flow in the transformer winding. If the current of double frequency has such a phase that its positive maximum strengthens the positive maximum of the fundamental current and weakens the negative maximum of the fundamental current, the curve of the resulting magnetizing current has a short high positive portion and a longer lower negative portion. This current produces a flux curve, the integral value of which differs from zero; which means, that the alternating magnetizing current produces a direct flux besides an alternating flux. This direct flux is however of no importance, because it neither produces an e. m. f. nor requires a direct current or a direct voltage for its maintenance. The direct flux is only an accompanying phenomenon, and does not support the formation of the double frequency.

In the following we shall see, that it is even not always necessary, that a direct flux exist. In consequence of the saturation of the iron core, the direction of the direct flux is either positive or negative. This fact quite depends on the phase of the double-frequency current. In the example, where the positive maximum of the double-frequency current strengthens the positive maximum and weakens the negative maximum of the fundamental current, the direct flux is negative in spite of the high positive current peak. For the positive current peak produces on the average only a little higher flux value than the lower negative current values; but the negative current values exist much longer than the positive current values, so that the integral value of the flux curve, and with this the direct flux, become negative.

If however, the phase of the double-frequency current is shifted about 180 deg., so that the positive maximum of the fundamental current is weakened and its negative maximum is strengthened, then the resulting curve of the magnetizing current has only a short high negative peak and a longer lower positive portion. This current produces a flux curve, the integral value of which is positive, that is, the direct flux is positive.

Between these two states, where the direct flux is either negative or positive, such a phase for the double-frequency current, where the direct flux is zero, can be found. Then there is neither a direct flux, nor a direct current, nor a direct voltage. In other words, there is nothing which may resemble a bias.

W. W. Edson: Could this feature of neutral instability, or the half and double frequency oscillations, have any probable effect on the following installations?

1. Three 8050/115-volt star-delta connected potential transformers operating watthour and power-factor meters.
2. Same except operating directional relays.
3. Similar except using two transformers connected open star/open delta. In this case it was found that the three voltages to ground on the secondary leads are unbalanced, that is, the neutral is outside of the secondary delta.
4. Three 110-kv. condenser bushing network potential devices in effect equivalent to star-star connected potential transformers operating directional relays connected in delta. An auxiliary set of three potential transformers is connected to this secondary circuit and is arranged star-delta with a ground directional relay in the corner of this delta.

Walter L. Upson: The three companion papers dealing with abnormal line-to-neutral voltages of a Y-Y system present an admirable attack on a rather difficult subject. The contrasting theoretical studies are of considerable interest inasmuch as they represent such entirely different approaches to the problem that a reading of either paper would hardly suggest the other. Messrs. Boyajian and McCarty have built up their argument on the combined saturation curves of inductance and capacitance in parallel forming one leg of a three-phase system. Mr. LaPierre has used an equivalent circuit in which a capacitance is placed in series with the three inductive phases of his system, one terminal of the condenser being connected to the

neutral while the other is anchored to the assumed fixed neutral of the three-phase system supply. With this picture in mind, he considers what may take place under the provocation of saturated transformer cores. The effect of saturation in any one transformer is to make its inductive reactance negligible in comparison with the other unsaturated transformers. There results a heavy flow of current through this transformer into the condenser. Most of the voltage drop of this phase is across the condenser which is then charged up in such a direction that its voltage more or less opposes, for the moment, that of the other two phases. In the course of cyclic variation of voltage on the transformers, we soon reach a point at which one of the previously unsaturated transformers becomes subjected to the condenser voltage in addition to its phase voltage, with the result that the condenser discharges, saturating this transformer and then becoming charged in the opposite direction.

If there is the proper balance between capacitance, percentage of normal transformer voltage and perhaps other less important factors, this proceeding will be repeated and will become periodically recurring or stable. Of course something must start the phenomenon, and the author takes this to be the abnormal condition brought about by the starting transient with or without the help of residual magnetism in the transformer core. When the stable condition is reached all three transformers have presumably been brought to the same magnetic condition in which saturation passes successively from one to another, each time being accompanied by a reversal of the condenser potential. It is rather difficult to form a picture of this changing condition which will include the four possible periodic frequencies of the phenomena and enable one to see why any one of the frequencies should prevail under a given set of conditions, in spite of the author's painstaking effort to make it clear. However, if we start with a sine wave of flux which we will assume to be produced by a suitable magnetizing current, we can lay off a sine wave voltage, e_t, impressed on the transformer and leading the flux by 90 deg.

Lagging by 90 deg. will be the voltage drop across the condenser, and the sum of these two voltages will be the phase voltage of the system. Now suppose saturation to occur near the peak of the flux wave and that the peak is therefore flattened out. The voltage, e_t, falls quickly to nearly zero at the instant of saturation, and remains there until saturation ceases. At the same time, the condenser voltage rises being retarded by the falling system voltage, but continuing to rise while the system voltage builds up in the opposite direction and the transformer voltage hovers around zero. As soon as saturation ceases, the transformer voltage rises to something of a peak. If the transformer now saturates in the opposite direction, the procedure will repeat itself as outlined above. If it does not saturate, the condenser, being unable to discharge will retain its potential, permanently inverting the neutral unless it finds opportunity to combine with one of the other transformers to produce saturation in it and build up a charge in the opposite direction. Mr. LaPierre's theory is no doubt correct, and is greatly clarified in the last section of the appendix. However, even here we are left without directions which would enable us to predict the type of oscillations which might be expected. This is probably due to the necessity for restricting the extent of the paper. It would be interesting if a series of actual oscillograms could be shown based upon predetermined constants and conditions of operation.

A. Boyajian and O. P. McCarty: Mr. Fallon arrived at almost the same results and broad conclusions as ourselves but considerably earlier and through an entirely different route. We are glad to acknowledge his priority, and are pleased with the agreement in opinions.

Mr. Lampert has indicated a difference of opinion with reference to the necessity for bias. We all probably will agree that the integrals of the fundamental and second harmonic fluxes (in fact, of all the integral harmonic fluxes) taken over a cycle of the lowest frequency will add up to zero regardless of their phase relation, as is almost axiomatic. The same statement would also be true about currents. However, that does not exclude the possibility of a bias like the residual, requiring no external magnetomotive force in the form of a continuous unidirectional current in the windings, and therefore not appearing in any current integral. If an inexact even harmonic, which is continuously changing its phase with respect to the excitation frequency, needs an alternating bias, as Mr. Lampert seems to agree with us, then, it would seem to follow that the exact even harmonic of such a phase as to require neither a positive nor a negative bias would not be permanent, because it would not be able to draw power from the fundamental frequency to supply its losses.

Undoubtedly, in complex phenomena such as discussed in this group of papers, there are points on which opinions will differ, but it is satisfying to note that there is general agreement on the broader physics of the subject.

As indicated in our paper, we do not consider the subject as completely analyzed and closed. Since submitting our paper, we have attempted also a mathematical approach to the subject, and hope to be able to present it to the Institute in the near future.

C. W. LaPierre: The interest Professor Upson has taken in the successive saturation theory of these phenomena is greatly appreciated. His discussion brings out one or two points which might well be clarified further.

In interpreting these phenomena it is important to keep in mind several prominent characteristics of the observed data. In the first place a large portion of the oscillograms taken indicate that the phenomena are highly irregular in their nature. In many of the oscillograms shown by Mr. Weller the fundamental frequency is almost completely obscured. In most of the oscillograms showing the transient state there is no evidence of any definite frequency being present. Instead the voltages take the form of an irregular series of voltage swings.

Such transient states are highly important and should not be ignored for they in general produce the largest surges and insulation strains. Furthermore the sustained voltages are not lacking in irregularities of one sort or another. This highly irregular character of the phenomena is generally recognized.

On the other hand, and in the second place, the observed data for the sustained conditions do indicate certain regularities which require explanation. Such characteristics are amply shown in the tabulations of both the other papers of this group.

The phenomena, therefore, present a two fold aspect. Under one condition, largely transient, they are highly irregular and occur without definite magnitude or frequency. Under another condition they occur in a quite definite manner and possess easily identified characteristics. It is this dual nature of the phenomena which caused me to adopt the method of approach so nicely described by Professor Upson.

The results of this method are somewhat unexpected in that the highly irregular transients are very easily explained by the theory developed. The sustained conditions appear as special cases of the irregular transients and occur under proper circuit conditions when the transients more or less accidentally fall into a permissible sustained frequency. Due to the element of chance which enters it is not so easy to picture as a direct result of cause and effect the transition from the irregular to the definite frequency. However, such a procedure is not necessary. If the generation of the transient voltages is understood and it is further understood just what the necessary conditions are for a stable succession of saturations then one may readily see how the transition occurs. As to whether it takes one, ten, or fifty cycles to complete the transition is of no theoretical importance provided the mechanism itself is clear. In general the successive saturation theory is devoted to an explanation of just these fundamental processes which underlie the abnormal voltages.

As a result of its application it has been possible to devote a complete section of the paper to the explanation of detailed characteristics of the observed data, both for transient and sustained conditions.

In the latter part of Professor Upson's remarks a description is given of the voltage changes during the saturation process. It is necessary here to consider the relative magnitudes of the various circuit factors entering into the phenomena. Professor Upson's remarks apply largely to the condition where the circuit capacitance is relatively small. In that case the voltage does fall "quickly to nearly zero" and remains there until saturation is completed.

However, the transformer voltage cannot drop to zero without upsetting the voltage distribution between the individual capacitances making up the system total. If the system capacitance is relatively large the abrupt voltage change requires a large surge of current which must be supplied from the saturated transformer. In such a case of saturation, when the transformer voltage does reach zero the current surge is at its peak. With no voltage to maintain it the current tends to drop to zero. Its abrupt decay is accompanied by a partial collapse of the transformer flux which carries the transformer voltage far in the reversed direction. It is this process which generates the large voltages which are regularly observed in these phenomena. In this manner we are able to deduce from Figs. 2, 3, 4 and 5 of my paper that the system capacitances associated with these phenomena are relatively large, for, in those illustrations the voltages pass abruptly through zero to their reversed values at each saturation. Of course there may be, and undoubtedly are, minor saturations occurring in such an irregular process which do result in reversed voltages hovering around zero for a time, but these minor saturations are incidental to the main process. The magnitude of the reversal depends almost entirely upon how far the voltage must drop to reach zero after saturation sets in.

C. T. Weller: In regard to Mr. Edson's question, the connection mentioned in his first two items is referred to in the first paragraph of the paper and also under the section "Secondary Connections." The performance of two potential transformers connected L/N is indicated in Fig. 16, which is supplemented by Table VI and by a descriptive paragraph on page 315. Bushing potential devices consist primarily of two capacitances in series, the larger capacitance (and lower voltage) being shunted by a potential transformer; saturation in the L/N circuit as a whole, therefore, is not involved, so the phenomena should not occur.

Mr. LaPierre called attention to the erratic wave shapes and frequencies of the L/N voltages obtained during the starting transients leading to the temporary or sustained establishment of the phenomena. However, it would appear logical to assign a definite phenomenon letter or frequency to a particular half-cycle (or more) during the transient period, if such a phenomenon or frequency were also obtained in sustained form under similar conditions. Since this was true in most cases, I assigned phenomena letters to transient approximations of sustained phenomena for convenience. In the few cases where the phenomenon so designated was not obtained in sustained form, it is evident from the dâta that a modification of the circuit constants not then possible would have produced the phenomenon in sustained form.

Until recently, there has been no special interest in the Y-connection of potential transformers, although a growing realization of its advantages for ground-protection schemes has led to its more extensive adoption. It was therefore in order to point out some of the disadvantages of the applications with grounded neutral to ungrounded systems, particularly since they did not appear to be generally known. The phenomena described in the paper first presented themselves as potential transformer disturbances, which were quelled by the addition of suitable protective resistor burdens. It was not appreciated at the time that somewhat similar phenomena had been encountered previously (with power transformers), so comprehensive tests were made; the essence of the data obtained is presented in the paper.

Certain terms adopted in the paper might be considered for general use. The advantages of substituting "L/L" for line-to-line and "L/N" for line-to-neutral are self-evident. Also, "broken delta" implies a three-transformer connection with the secondary delta circuit either open or closed through a comparatively high-impedance device; a differentiation from "closed delta" and "open delta" (for two transformers) is thus obtained.

Figs. 2c and 2d and even 2b might be criticized because distorted wave shapes or harmonics cannot be represented properly by means of vectors. However, unusual phenomena justify unusual treatment and it is believed that the figures convey a fair idea of the effects of neutral displacement on the L/N voltages. A figure representing triple-frequency Phenomenon D was not included as this phenomenon was obtained only in transient form with potential transformers, although the transient L/N voltage crests were definitely higher than for double-frequency Phenonenon B. Even in the somewhat special case with distribution transformers, D was obtained in semi-sustained form only. Also, a figure representing the well-known third-harmonic phenomenon, due to suppressing the corresponding harmonics of the exciting currents, was not included. The apparent disregard of the effects of this well-known phenomenon afforded a convenient means of introducing the less-known phenomena.

The excellent reproductions of the oscillograms in the paper require no group comments when the sections are printed together. However, it was not possible to print three or four sections together, so descriptive references in the text to wave shapes shown "at the right" of the oscillograms or "subsequently" should sometimes be interpreted as "below." An inspection of the wave shapes of the "exciting" or line currents, which combine to form the neutral-to-ground current, and a consideration of the relative magnitudes involved will indicate why the phenomena were known from the first to be "saturation phenomena."

There are several points in the paper that require further emphasis. It should be noted that the phenomena are not characteristic of any particular ungrounded system or type of transformer. Phenomena B, C and D endanger the potential transformer themselves; B and D endanger other connected equipment also. All phenomena tend to cause incorrect synchronizing and incorrect relay operation.

The "General Recommendations" are intended as an approximate guide in the application of Y-connected potential transformers. It should be noted that it is possible to obtain the phenomena below 50 per cent of rated voltage, but that such an occurrence in practise is extremely improbable. The L/N voltage rating referred to in Table IV and elsewhere in the paper covers a somewhat special design of transformer, which can operate temporarily at L/L voltage in an emergency.

In conclusion, it is believed that a reasonably complete picture of the "saturation phenomena" is presented for the first time. While a review of the companion papers will indicate that the theory is somewhat complicated, there is no question as to what should be done to prevent the occurrence of the phenomena. In all cases, adequate secondary protective resistor burdens only are necessary; the magnitude of these burdens is related to the rating of the potential transformers and to the flux density at which they normally operate. The paper will have accomplished its purpose if it contributes to a better understanding of the operating difficulties involved and so prevent the inadvertent application of grounded-neutral, Y-connected potential transformers to temporarily or permanently ungrounded systems.

Power Transformer Noise
Its Characteristics and Reduction

BY ROBERT B. GEORGE*

Member, A. I. E. E.

Synopsis.—Audibility characteristics of the ear and the units used for measuring noise are briefly discussed. A theoretical investigation was made to determine the different force components and other causes of transformer hum. Surface vibration measurements were made on transformer parts to determine the sources which cause noise in transformers and how these noise sources are affected by variations in operating conditions. Noise surveys were made to measure the range of intensities, the frequency characteristics and distribution of sound from transformers in service. The effects of substation acoustic conditions on noise distribution were investigated.

CONSIDERABLE attention is being given to the reduction of unnecessary noises emitted by electrical apparatus. The scope of this paper is intended to cover the progress which has been made in the reduction of noise in power transformers. It represents only a part of an extensive investigation which is resulting in quieter electrical apparatus.

Practically all types of sound which cannot be classified as speech or musical tones may be classified as noise. Since transformer noise sounds like a hum having a definite pitch, it may also be classified as a musical tone. This tone may not be objectionable for short periods of time but when it is heard continuously for long periods of time it may be objectionable to some people.

The occurrence of sound involves the action of three elements,[1] the sound generator which is essentially a vibrating body, the transmitting medium and the sound detector. The vibrating body sends out simple harmonic pressure waves in all directions. These waves are transmitted by the air (or other medium) which surrounds the vibrating body. If the ear is placed in the sound field so that it may be acted upon by the incident pressure waves, the diaphram of the ear will be set in vibration by the alternating pressure. For a given frequency the apparent loudness is approximately directly proportional to the logarithm of the r. m. s. sound pressure. Fig. 1, which is the result of the work of Bell Telephone Engineers,[2] shows the maximum and minimum limits of audibility as a function of sound pressure and frequency. The minimum audibility curve is an average for many observers and corresponds to perfectly quiet conditions. If ordinary room noises were present, the lower audibility limits would be much higher than the values for this curve. Fig. 1 indicates that the ear is most sensitive to sounds having a frequency of approximately 3,000 cycles per second and the sensitivity decreases for sounds above or below this frequency.

In order to deal effectively with the noise problem, the sound analyzer developed by Mr. J. P. Foltz[3] was used in these investigations. The set[4] consists principally of a set of amplifiers and filter circuits which can be set to eliminate all but a certain frequency. The noise to be analyzed is picked up by a microphone and passed through the filter circuits. The setting of the filter circuit condenser indicates the frequency of the sound to be measured, and a meter indicates the intensity of the sound at that frequency in dynes per sq. cm. One dyne per sq. cm. equals approximately 0.00000035 lb. per sq. in. Dynes per sq. cm. are absolute units which are independent of the local noise level.

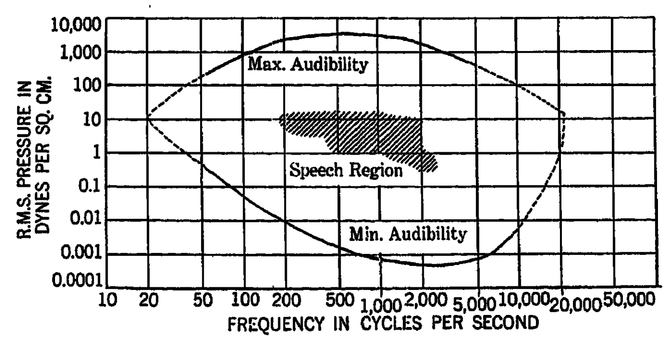

FIG. 1—MAXIMUM AND MINIMUM LIMITS OF AUDIBILITY

It is not desirable to make sound tests on comparatively quiet apparatus where the local noise level is high.

This analyzer is independent of the human ear for comparing sounds with reference standards, and it leaves nothing to personal judgment or the imagination of an individual listening to a telephone receiver.

A transformer has no rotating parts. An impulse from each half cycle results in a fundamental frequency of vibration of 120 cycles (double vibrations per second) from a 60-cycle transformer. These vibrations usually originate in the core and coil structure and are transmitted by the oil to the tank where they are in turn passed on to the air. When it is necessary to measure mechanical vibration, a calibrated phonograph pickup may be substituted for the microphone, and the sound

*Transformer Engineering Department, Westinghouse E. and M. Co., Sharon, Pa.

1. Churcher and King, *I. E. E. Journal*, Vol. 68, January, 1930.

2. "Useful Numerical Constants of Speech and Hearing," Fletcher, *Bell System Technical Journal*, Vol. IV, July, 1925.

Presented at the Southern District Meeting No. 4, of the A. I. E. E., Louisville, Kentucky, November 19-22, 1930.

3. *Study of Noises in Electrical Apparatus*, Spooner and Foltz, A. I. E. E., TRANS. July, 1929.

4. "Diagnosing a Case of Noise," J. P. Foltz, *Electric Journal*, March, 1930, p. 178.

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analyzer can be used to measure the frequency and amplitude of vibration. Since the active area, the frequency and the amplitude of vibration are related to the total noise emitted by the transformer at that frequency, the vibration of the tank surface can be measured on the test floor when the corresponding limits of vibration are known for satisfactory quiet operation in service.

A theoretical investigation was made to determine the different force components which might cause vibration, and to devise methods of dealing with each of these forces.

1. The force between the winding and the core is an attractive force, but when solid insulation is wedged in between the coils and core, this force is not serious.

2. There is an attractive force which acts at each joint of the core and tends to make the iron circuit continuous. This force is directly proportional to the cross section area and to the square of the magnetic density.

3. There are forces of repulsion between parallel laminations of the core. This is explained by the fact that like poles are induced in adjacent ends of parallel laminations.

4. There are electro-dynamic forces between the coils. These forces are attractive between coils of the same winding and repulsive between coils of different windings. These forces are proportional to the square of the ampere turns per group.

5. In addition to the forces enumerated above, metal plates, tie rods, radiator tubes, structural steel parts, or other members may be resonant and serve as unexpected sources of noise. These are sometimes very troublesome. It is very fortunate indeed, that power transformer tanks with large areas exposed for radiating sound, usually have natural periods of vibration below 60 cycles.

Some of the usual methods of obtaining quiet transformers consist of: (1) Using additional iron in the core in order to secure low magnetic density. This also means additional copper and a more expensive transformer. (2) Stiffening the bracing and supporting parts to reduce vibration and in some cases adding damping devices to change the natural period of vibration. (3) Adding cushions or padding between parts of the transformer.

Surface vibration measurements were made on the core and coil parts of several different transformers to determine the sources of noise due to excitation voltage only. The mid point of the high-voltage winding was grounded and the transformer was excited at 60 cycles, with 100 per cent voltage on the low-voltage winding during these tests. Vibration amplitude measurements were also made on the parts involved at no load and at different voltages between 80 and 120 per cent of rated voltage.

Vibration amplitude and frequency measurements were made on the tank surfaces of a number of representative sizes of completely assembled transformers at no load and at different voltage values. Then tests were made to determine the effect of line voltage regulation on the amplitude of vibration and the corresponding sound intensity. Fig. 2 shows the results of some of these tests on a large transformer at the elevation of the center of the core. The locations of the points are indicated on the plan view at the upper left hand corner of the figure. These curves are approximately straight lines within the operating range of the transformer. This indicates that the component due to voltage regulation can be considered to be directly proportional to the per cent change in line voltage for the region where these curves are straight lines. The ratio varies with different designs but it is usually of the order of 30 per cent change in sound intensity for 10 per cent change in primary voltage at no load.

Tests were made on the core and coil parts of a transformer to determine the characteristics of the parts of the transformer which serve as sources of noise due to load currents in the windings. These tests were made with one winding short-circuited and with sufficient voltage impressed on the other winding to obtain the desired values of load current in the windings. Vibration amplitudes and frequency measurements were made for each load condition. Similar tests were made on completely assembled power transformers and surface vibration measurements were made on the tank and other exterior surfaces. The curves of Fig. 3 show the effect of load current on the amplitudes of vibration of four representative points at different elevations on the side of a large transformer. It can be observed that the amplitude of vibration varies approximately as the square of the load current.

Tests at varying frequency were not made on large power transformers on account of the inconvenience of obtaining sufficient power at adjustable frequency.

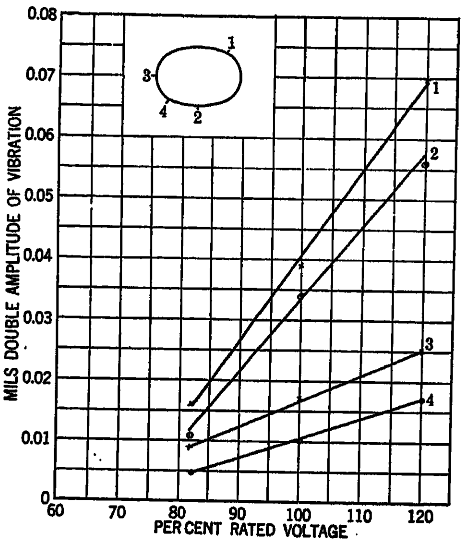

Fig. 2—Curves showing the Effect of Voltage Variation on Amplitude of Tank Surface Vibration

Such tests are useful for determining resonant frequencies of various parts but they do not represent operating conditions on a constant frequency system.

Frequency analyses were made of points of maximum amplitude of vibration, with the transformer operating at rated frequency. Fig. 4 is a frequency analysis of

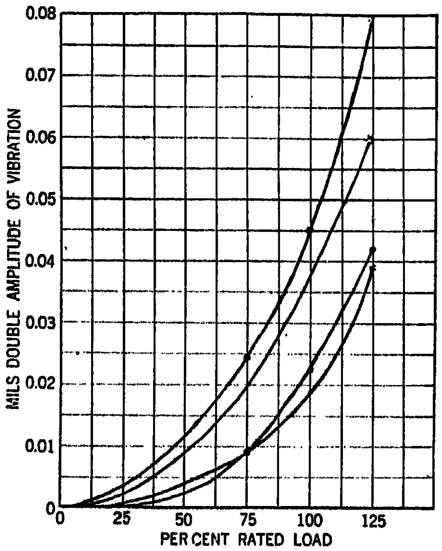

FIG. 3—EFFECT OF LOAD CURRENT ON AMPLITUDE OF TANK SURFACE VIBRATION

vibration of the point of maximum amplitude of vibration of a 60-cycle transformer at 100 per cent voltage and no load. Fig. 5 is a frequency analysis of the same

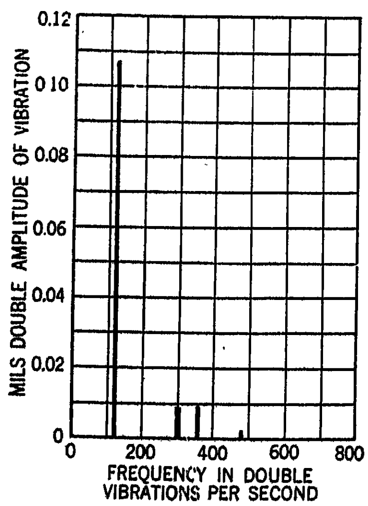

FIG. 4—FREQUENCY ANALYSIS OF VIBRATION AT 100 PER CENT VOLTAGE AND NO LOAD

point with the transformer at 150 per cent load current but without excitation.

It is interesting to note that different harmonic frequencies are present during the two conditions. This is evidently due to different parts of the transformer being affected by the load and the excitation components. All of these harmonic frequencies are exact multiples of the 60-cycle power frequency. The test range included frequencies up to 3,000 double vibrations per second but no frequencies above 600 double vibrations per second were noted.

The vibration amplitudes of this transformer at frequencies above the fundamental 120 cycles are so small that they can be neglected. There have been a few

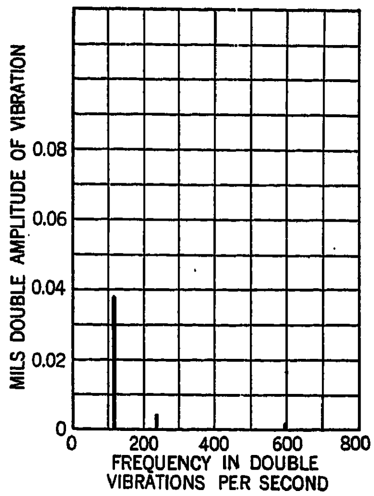

FIG. 5—FREQUENCY ANALYSIS AT LOCATION OF FIG. 4 EXCEPT AT 150 PER CENT LOAD CURRENT AND WITHOUT EXCITATION

cases, however, where harmonic frequencies were appreciable and it was necessary to weigh them in proportion to the audibility curve of Fig. 1.

Noise surveys were also made to measure the range

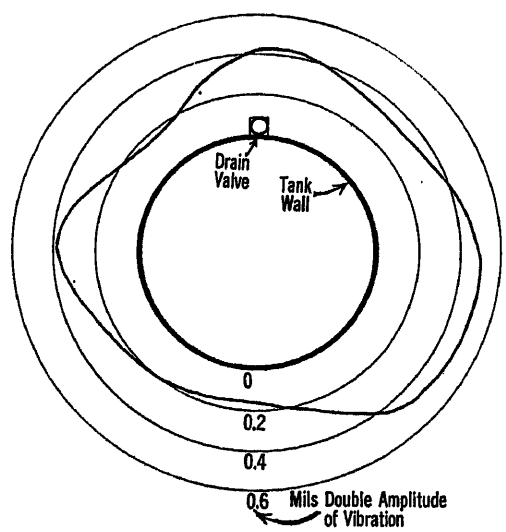

FIG. 6—DISTRIBUTION OF VIBRATION AROUND THE TANK OF A LARGE POWER TRANSFORMER

of intensities, the frequency characteristics and distribution of sound from power transformers in actual service.

Complete vibration measurements were made of the tank surfaces of each transformer where sound measurements were made, in order to obtain data on the relation of vibration of the tank surface to the sound given off by the transformer.

Fig. 6 shows the vibration of the tank wall of a 60-

cycle transformer at 97 per cent voltage and 41.6 per cent load. The curve is plotted in polar form with reference to the tank wall and at greatly enlarged scale in order to show the distribution of vibration.

Fig. 7 shows the distribution of the sound intensity of the 120-cycle fundamental note measured at a distance

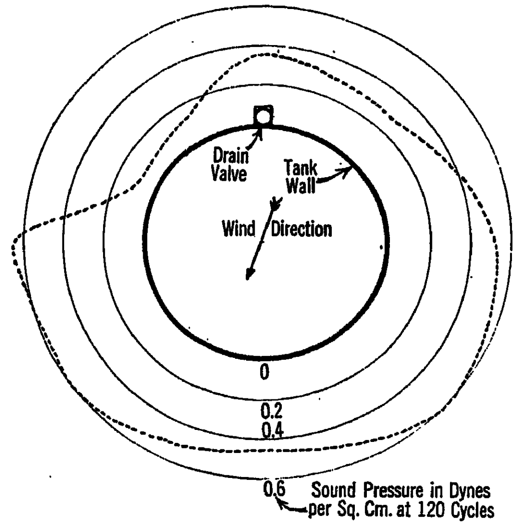

FIG. 7—DISTRIBUTION OF 120-CYCLE SOUND INTENSITY MEASURED AT 10 FT. FROM TANK WALL

of 10 ft. from the tank wall. There is a marked similarity between the distribution of vibration amplitude and the distribution of sound intensity. The substation structures at the upper left hand corner account

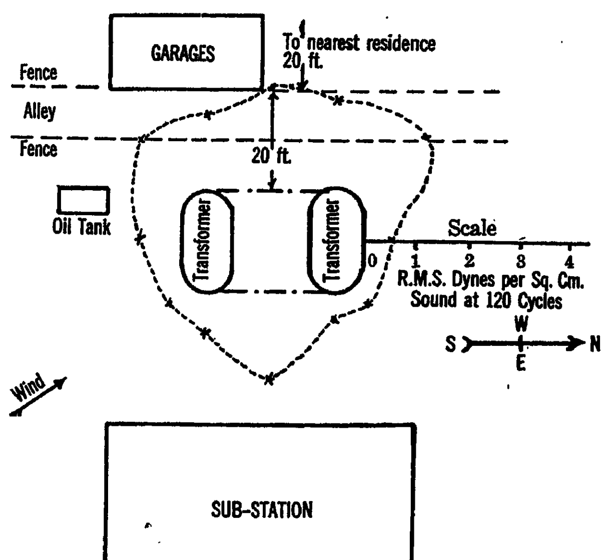

FIG. 8—DISTRIBUTION OF 120-CYCLE SOUND AT 20 FT. FROM TRANSFORMERS

for the sound distribution in this region and the wind blowing from the direction indicated in the figure accounts for the increased sound intensity in the lower left hand region of the figure.

Fig. 8 shows the distribution of sound at 120 cycles measured at a distance of 20 ft. from the transformers of Fig. 9. Since there are two transformers in this station, lines are drawn to connect the two transformers and the resulting area is treated as the noise source. The curve is plotted similar to polar form with reference to the tank wall and the two connecting lines described above. At a distance of 20 ft., the average intensity is

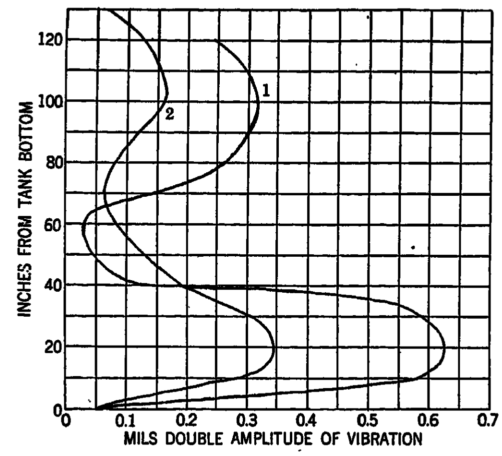

FIG. 9—VIBRATION ALONG VERTICAL LINES AT THE SIDES OF TWO LARGE TRANSFORMERS

1.142 dynes, the minimum intensity is 0.48 and the maximum intensity is 2.06 dynes per sq. cm., or a maximum to minimum ratio of 4.3 to 1. Reflections from the substation building and the neighboring garages are evident. The effect of wind is also evident in the upper right hand corner of the figure.

Curve 1 of Fig. 9 shows the distribution of the

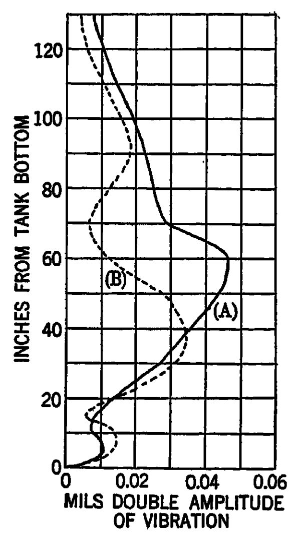

FIG. 10—VIBRATION ALONG VERTICAL LINE OF TANK.

(A) Complete Transformer
(B) With tie plates removed

vibration up the north side of the north transformer, and curve 2 shows the condition on the south side of the south transformer. Both transformers are large three-phase units and the load conditions are approximately 97 per cent voltage and 83.6 per cent load.

Curve *A* of Fig. 10 shows the distribution of vibration

up the nearest side of the transformer of Fig. 11. Since this is an unusually quiet transformer, the amplitudes are plotted to a larger scale. It is also of interest to note that the difference between curves *A* and *B* of Fig. 10 indicate a possible further reduction which can

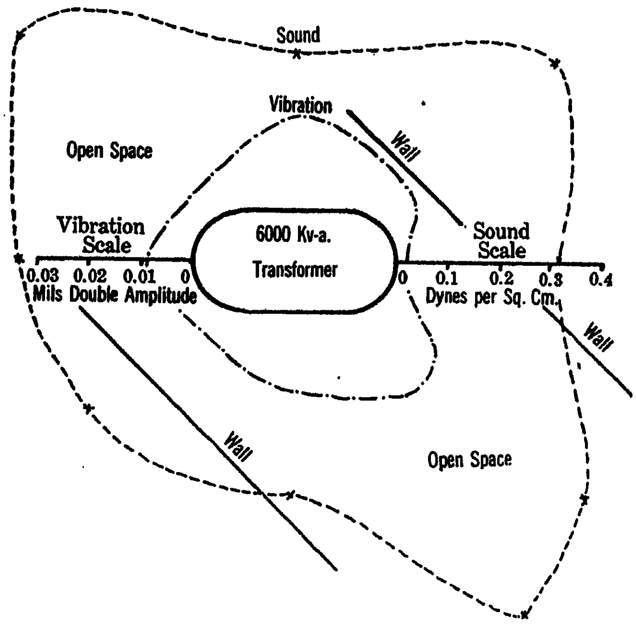

FIG. 11—DISTRIBUTION OF TANK WALL VIBRATION AND DISTRIBUTION OF 120-CYCLE SOUND PRESSURE AT 42 IN. FROM TANK WALL

be accomplished by removing the steel plates which brace the core and coils to the tank wall. This practise is not generally recommended except in cases where the transformer will not be moved before the oil is lowered and the steel plates replaced.

Another interesting illustration of the effects of the acoustic conditions at the substation is given in Fig. 11.

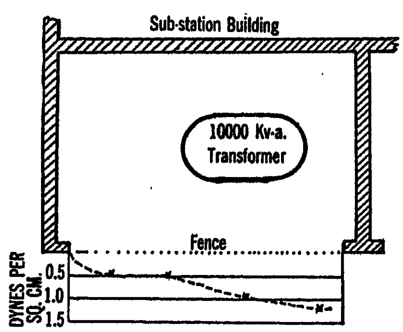

FIG. 12—DISTRIBUTION OF 120-CYCLE SOUND PRESSURE ACROSS THE OPEN SIDE OF A TRANSFORMER COMPARTMENT

A smooth finish plastered wall was located diagonally as shown on the upper side of the figure and a hard surface wall of steel plates was located symmetrically on the opposite side of the transformer. The inner curve shows the distribution of vibration of the tank wall at 120 cycles and the outer curve shows the distribution of the intensity of sound at 120 cycles, and at a distance of 42 in. from the tank wall. Both curves are plotted similar to polar form with reference to the tank wall. The average 120-cycle intensity is 0.385 dynes per sq. cm. The maximum is 0.685 and the minimum is 0.31 or a maximum to minimum ratio of 2.2 to 1.

After the sound measurements for Fig. 11 were completed the transformer was deenergized, and the room 120-cycle noise levels at 42 in. from the two ends of the transformer, were found to be 0.152 and 0.162 dynes per sq. cm. respectively. This indicated that approxi-

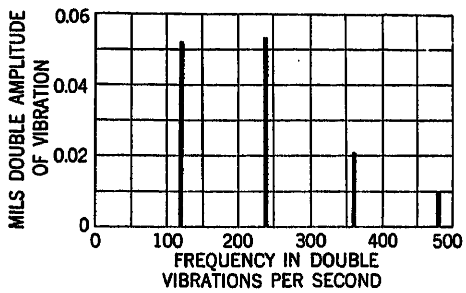

FIG. 13—VIBRATION ANALYSIS AT MID POINT OF TRANSFORMER SIDE WALL

mately one-third of the sound curve of Fig. 11 represented external noise which did not come from the transformer.

The distribution of sound at 120 cycles measured across the open side of a compartment 32 ft. wide and 22 ft. deep is shown in Fig. 12. The three walls were smooth surface brick with a glass window and glass door into

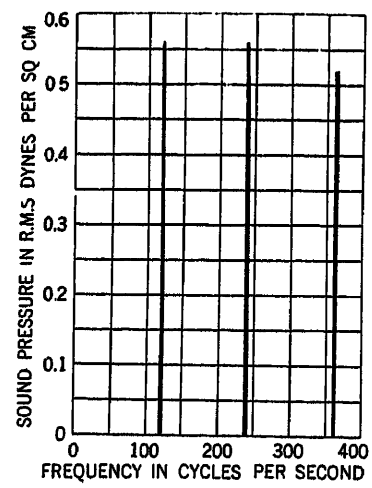

FIG. 14—SOUND ANALYSIS AT 10 FT. FROM TANK WALL AT LOCATION OF TESTS FOR FIG. 13

the substation building which formed the rear wall of the compartment. The 120-cycle sound intensities at the curb on the opposite side of the street, (approximately 50 ft.) were 0.0497 and 0.0416 dynes per sq. cm. opposite the left hand and right hand walls respectively.

Fig. 13 is a vibration analysis at the midpoint of the tank wall nearest to the open side of the compartment and Fig. 14 is a sound analysis at the center of the open side of the compartment.

Fig. 15 is a sound analysis made at a distance of 10 ft. from the drain valve of a transformer. When the distance was increased to 50 ft. from this transformer, the sound intensity was only 0.05 dynes per sq. cm. at the fundamental 120 cycle note and no higher frequencies could be detected.

On account of the very nature of a transformer, it will always have some hum, but this hum can be reduced for operation near hospitals or in residential districts. A quiet transformer is really a relatively quiet transformer. Part of the noise can be eliminated by adding refinements at a slight increase in cost and each further reduction in noise is obtained at the expense of more material and additional cost. The conditions are similar to obtaining high efficiencies, first by refinements to reduce the stray losses and finally by working the materials at lower densities to obtain the economical balance between the additional cost and the value of reduced losses.

These and other investigations also indicate that the sound intensities are not equal in all directions from the

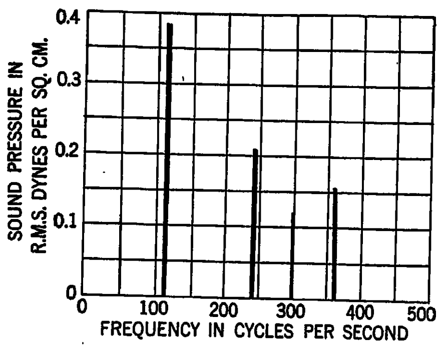

FIG. 15—SOUND ANALYSIS AT 10 FT. FROM A TRANSFORMER

transformer. Reflections from local objects near the substation cause wide differences in intensity at different points near a transformer, although at equal distances from the tank wall. The acoustic conditions at the substation can make a relatively quiet transformer appear to be noisy. For example, two converging walls or a corner can give directional effects similar to a megaphone. Some foundations, walls or objects can act as sounding boards. Oil lines, conduits or particularly sheet metal parts at the installation may have resonant frequencies which may cause them to emit noise.

If sufficient area is used to prevent crushing, cork pads are effective under transformer tanks in indoor vaults. Arbors, hedges, shrubbery and trees are very effective for absorbing sound from outdoor substations.

CONCLUSION

In addition to critical vibration frequencies of various metal parts, there are two distinct components which cause noise in power transformers. The load component varies as the square of the load current; the excitation component varies approximately 3 per cent for each per cent change in line voltage within the usual operating range, but this ratio and the proportions of load component to excitation component vary with different designs.

The surveys provide considerable advances in the knowledge of power transformer noise characteristics and magnitudes. The sound intensities are not uniform in all directions from a transformer, and the acoustic conditions at the substation play an important part in the final distribution of the sound. Our knowledge of this problem has not reached the stage where we can definitely predict in advance the sound emitted by a transformer, particularly since surrounding conditions are so important. Tools and methods have been devised for making further progress.

ACKNOWLEDGMENTS

The writer wishes to acknowledge the work of Mr. J. P. Foltz, Research Engineer, who developed the vibration meter and sound analyzer which made this work possible. Mr. Foltz also assisted in making the tests. The writer also wishes to acknowledge the cooperation and assistance of members of the Pennsylvania and Ohio Power Co., and Detroit Edison Co., in making the surveys of transformers in service.

Discussion

F. W. Gay: The question of noise as related to electrical equipment is becoming of increasing importance and methods of reducing noise, or eliminating noise, will in the future receive correspondingly increased consideration. Mr. George does not bring out one very important point regarding the question of noise in electrical equipment; this point is the *time element.* During busy periods of the day and early evening, noise in electrical equipment is by no means as objectionable as during the quiet hours of the night. Fortunately the loads on electrical equipment during the quiet hours are relatively light and this fact at once suggests the advisability, if practicable, of lowering the densities at which materials are working during these light load periods.

A method which would seem practical if switching schemes were properly worked out, would be that of operating the transformer windings in series during light load periods, and in multiple during heavy load periods. As an example of such operation, if it be assumed that the transformer illustrated in Fig. 2 of the paper is operating at a core density of 11,000 gausses, a reduction to 7,500 gausses would represent a reduction to less than 70 per cent of normal density. Such a reduction, according to the curves shown in Fig. 2, would reduce the noise to very nearly the vanishing point, while the noises due to load as shown in Fig. 3 would not be serious during light load periods.

Now, if a transformer were designed for 7,500 gauss operation at light load with windings in series, and 15,000 gauss at heavy load with windings in parallel, such a piece of equipment would have an increased capacity of approximately 36 per cent and would only need to be operated in multiple for a few hours per day, or perhaps not at all for long stretches in the summer time when loads are generally light and noise is very objectionable.

A transformer designed for such series multiple operation could be operated to give a much higher average efficiency as well as very little noise during light load periods, and would have the added advantage of greatly increased overload capacity during periods of emergency.

Another method of practically eliminating noise would be to fully enclose the electrical equipment in noise-proof compartments and, in the case of transformers, resort to cooling by

radiators placed on the roof, using a volatile fluid to carry the heat from the transformer oil to the radiators on the roof. Such methods of carrying off heat have been used heretofore but have proven impractical by reason of the fact that the heat was dissipated from the radiators at only one temperature. It is suggested that several bodies of volatile fluid be used, each sealed separately from the others. One such body of volatile fluid may absorb heat at a high temperature from the oil at the top of the transformer tank and dissipate such heat from a radiator system on the roof at a corresponding high temperature while another body of volatile fluid may absorb heat from the oil at the bottom of the transformer tank at a low temperature and dissipate such heat from the radiator located on the roof at a corresponding low temperature.

A very great advantage can be obtained in the use of such a system of cooling, inasmuch as the radiator system dissipating heat at a high temperature need not receive air warmed by previous cooling operations as is necessarily so when the radiation devices are located around the transformer, and of necessity those radiation devices located at the top of the tank and adapted to radiate heat at a high temperature are bathed by hot air which has previously served to cool the lower portions of radiating surface which are radiating at a lower temperature.

This paper represents one of the first steps, which must be followed by practical design changes before the manufacturers can produce electrical equipment adapted to meet the probable exacting demands of the future.

Design changes should, if possible, be made in such a manner that not only will the noise be reduced, or eliminated, but other advantages will accrue which will at least in part compensate for the increased expense involved.

It would appear that there are many ways of reducing noise, some of which if properly worked out will produce equipment having better average efficiency, greater maximum capacity, smaller floor space dimensions, etc. These will go a long way to compensate for other disadvantages which must necessarily follow in departing from a design which has been so well worked out as the present oil-immersed self-cooled transformer.

W. W. Edson: As mentioned in the paper the noise from power transformers adjacent to a building is frequently quite troublesome, especially in a residential neighborhood. One solution which still appears to be satisfactory after several years' service places the transformers in a pit in front of the station. The noise is reflected upward and is not noticeable to the residents across the street.

R. B. George: The condition Mr. Gay calls the time element is really the combination of light load and a slightly higher voltage applied to the transformer terminals due to lower voltage drop in the line between the generating station and the transformers. The noise due to load current, illustrated by Fig. 3, is usually negligible for this condition. The effect of increased voltage, illustrated by Fig. 2, causes a slight increase in sound intensity from the transformer. When the traffic noise ceases in the vicinity, it may be possible to hear the transformer. Equipment for changing transformer taps under load can be used to control the voltage delivered to the transformers to obtain noise reduction by taking advantage of the characteristics illustrated in Fig. 2.

Both of the schemes described by Mr. Gay should be effective for reducing noise, but the writer favors simplicity in the apparatus and giving more attention to the acoustic conditions at the substation. Mr. Edson's scheme of placing the transformer in a pit should be effective. When this scheme is used, there should be no roof above the pit. There is, however, a possibility of the building walls at the sides above the pit serving as reflective surfaces which may reduce the effectiveness of a shallow pit. When a transformer is placed in a pit, it may be necessary to provide additional ventilation for cooling.

I wish to add that felt, cork, and other sound absorbing materials which are effective at frequencies above 500 cycles are not very effective for absorbing the low frequency 120-cycle note of a 60-cycle transformer.

One of the most effective schemes known to the writer consists of building four walls of either asbestos board, cork, pressed fiber board, or preferably more substantial material built similar to a chimney, extending to several feet above the top of the transformer, and serving to direct the sound upward.

Governor Performance During System Disturbances

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R. J. CAUGHEY,* Non-member
E. M. HUNTER,* Associate, A. I. E. E.
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Synopsis.—This paper describes short-circuit tests which were made on a large power system under normal load conditions, in order to ascertain the operating characteristics of the system and the turbine governors during system disturbances. The introduction gives a brief description of the main features of the station and the connected system, a statement of the tests, and a list of the major conclusions. Part I covers the short-circuit tests on the system to determine the stability limits. Part II describes the load transfer and short-circuit tests to produce "governor pumping." Part III deals with the short circuits which were made to investigate the effect of a special valve mechanism on the stability limits. Part IV contains a discussion of miscellaneous tests, data, and general comments. In appendixes A and B, a detailed description of the system station and test equipment is given with estimates of the stability limits and short-circuit currents to be expected. Appendix C deals with the theory of the change in speed of a rotating body for a given energy differential.

* * * * *

INTRODUCTION

IN the past few years, the amount of analytical and test work on system disturbances and stability has increased tremendously, but very little of this theoretical or practical activity has dealt with the operation of steam turbine governors. Therefore when field tests appeared advisable to determine the cause of trouble evidenced by overspeeding and consequent tripping of the emergency overspeed governors on the

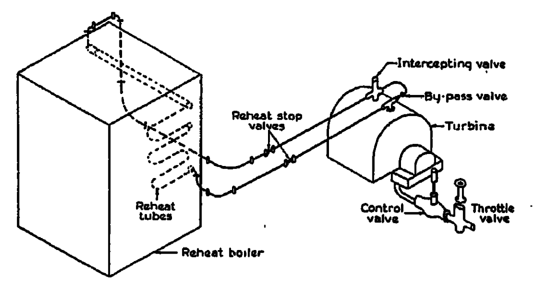

FIG. 1—SCHEMATIC DIAGRAM OF PIPING AND VALVES OF STANTON TURBINES

two 50,000-kw. single-cylinder reheat type turbines at the Stanton Steam Plant during the lightning seasons of 1928 and 1929, this opportunity was used to make a thorough investigation of the operation of turbines during system disturbances.

This plant is located near Pittston, Pa., and is jointly owned by the Scranton Electric Company and the Pennsylvania Power and Light Company. The steam connections and valves of the turbine are shown schematically in Fig. 1. All governing is normally done by the main control valve at the first stage of the turbine. Each generator has its own transformer bank and 66-kv. bus. Power is normally supplied by generator No. 1 to the Scranton Electric Company, and by generator No. 2 to the Pennsylvania Power and Light Company. The 66-kv. buses are tied together by a bus-tie reactor. Due to this reactor, generator No. 1 tends to swing with the Scranton Electric system and generator No. 2 with the Pennsylvania Power and Light system.

Fig. 2 and Fig. 3 show a one line diagram of the two systems and of the stations respectively. Further details of the system, station, and test equipment will be found in Appendix A.

More than fifty tests were made during this investigation, which was started in July 1929 and continued over a period of several months.

The decision of an operating company to make tests involving major system disturbances is based on the reasoning that such disturbances are a recognizable part

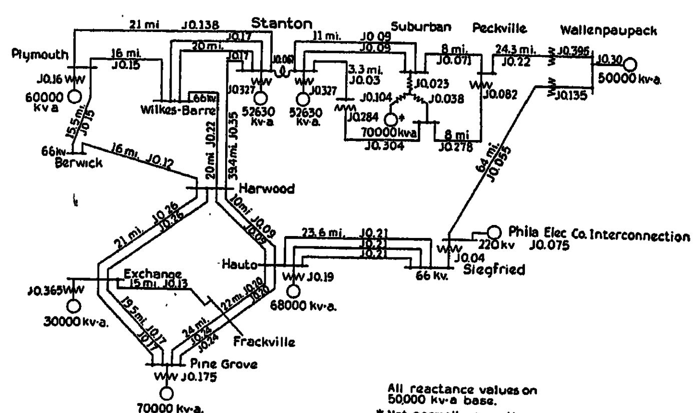

FIG. 2—ONE-LINE DIAGRAM OF PENNSYLVANIA POWER & LIGHT AND SCRANTON ELECTRIC COMPANY'S SYSTEM. ONLY EQUIVALENT CIRCUITS SHOWN FOR SOME PARTS

of normal operating experience and that these disturbances must be understood in order to insure safe and intelligent operation of any system. The best method for obtaining this information quickly is by actually carrying out a set of previously planned tests that will duplicate normal conditions.

GENERAL SUMMARY OF RESULTS

The results obtained shed additional light on some phenomena which have occurred during system dis-

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turbances and lead to the following general conclusions:

1. It is possible for a generator to lose synchronism and pull back in again without giving any conclusive evidence in the control room or at the turbine that such a change has occurred. Graphic charts and indicating instruments are not fast enough to indicate out-of-synchronism conditions reliably. Thus, this condition occurs far oftener than has been generally appreciated.

2. Cases of sustained system oscillation, or surging, seldom occur unless some generator, or group of generators, loses synchronism. Any oscillation resulting from a disturbance that is not sufficiently severe to cause loss of synchronism quickly dies out, due to the inherent system damping.

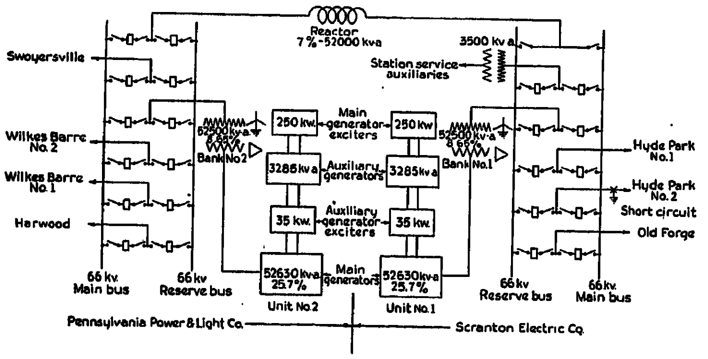


FIG. 3—ONE-LINE DIAGRAM OF STANTON STATION. REACTANCE VALUES EXPRESSED ON APPARATUS KV-A. BASE

3. Governors properly designed and adjusted will not contribute to any system oscillation as long as synchronism is maintained. When out of synchronism, however, the governor attempts to follow the speed change as the generator slips poles, and the result is a "pumping" phenomenon familiar to many station operators. This pumping action is a result rather than a cause of a sustained oscillation and is to be expected when the generator and the system are out of step at a certain slip frequency. It will cease if the generator pulls back into synchronism.

4. The speed of the turbine when out of synchronism is determined by the regulation of the governor and the induction generator characteristics of the generator. The average output during this period may be an appreciable portion of the output before loss of synchronism.

5. In these tests the short circuits resulted in considerable reduction in the kilowatt output of the generators with consequent overspeeding and loss of synchronism. Special valve equipment for quick reduction of steam input following a sudden drop in generator output will increase the stability limits. Under certain conditions it may be of considerable benefit in maintaining stability, but under other conditions the equivalent improvement in stability may be better obtained by other means.*

Part I

STABILITY LIMITS DURING SYSTEM SHORT CIRCUITS

Some preliminary tests were made by dropping and picking up load on one of the turbines to be sure that the governor and all other equipment was functioning correctly under normal conditions of system operation; these tests did not indicate anything erratic in the operation.

As short circuits were to be placed on one of the lines to the Scranton Electric Company from the 66-kv. bus supplied by generator No. 1, calculations were made to determine the magnitude of the fault currents and the stability limits of the system under short-circuit conditions. Fig. 4 shows the results of these preliminary calculations, which indicated that the system would be stable with a one-conductor-to-ground short circuit, but unstable with a two-conductor-to-ground short circuit, when the generator was carrying full load. These calculations also showed that if the load on the generator was reduced to 25,000 kw. and the short circuit was cleared in less than ¾ second, the system would be stable. The tests verified the calculations. For further discussion of the basis of these calculations, refer to Appendix B.

Test No. 11. The first short-circuit test consisted of a single-conductor-to-ground short circuit on the 66-kv. bus associated with generator No. 1. The auxiliaries for No. 1 turbine were supplied from the station transformer bank instead of from the house generator on this turbine, so that the full electrical output of the turbine would be effected by the short circuit. The voltage regulators on the main generators were left in service. Fig. 5 shows the resultant kilowatt swing in the output

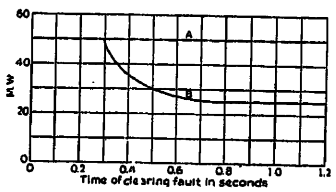


FIG. 4—POWER GENERATOR NO. 1 CAN CARRY AS A FUNCTION OF SWITCHING TIME

A. Rated mega watts of turbine
B. Two-conductor-to-ground fault outside generator transformer
Note: With a single-conductor-to-ground fault the stability limit is above rating of generator

*Such special valve equipment will vary in complexity with the size and type of the turbine and may be considered inadvisable for certain types. Its application to existing turbines may require a redesign of the valve controlling mechanism and the oil pressure system in order to get the necessary valve closing time of ⅛ to ¼ of the time at present required for normal governor operation. This equipment performs a function entirely different from that of the turbine speed governor and is not to be considered as a necessary adjunct to it.

of this generator. There was practically no movement of the governor beam during this short circuit and consequently no change in the steam input to the turbine. It should be noted that the inherent system damping caused the oscillation of the generator to die out very quickly. The short circuit caused a momentary reduction from 38,000 kw. to 25,000 kw. in the output of the turbine.

As predicted by the calculations and evidenced by

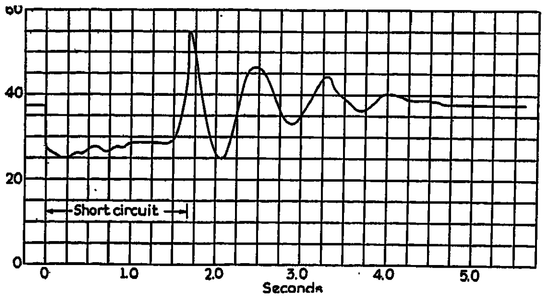


Fig. 5—Test 11. One-Conductor-to-Ground Fault. Both Generators Stable

this test, a much more severe short circuit would have to be imposed on the system in order to produce the instability of generator No. 1 which had been experienced during lightning conditions. All the following short-circuit tests were, therefore, two conductors to ground.

Test No. 12. Fig. 6 shows the record obtained from the next short-circuit test. The output of generator No. 1 was reduced from 40,000 kw. to 22,000 kw. and the generator pulled out of synchronism with the rest of the system before the short circuit cleared, but generator No. 2, which was carrying a load of only 31,000 kw., did not pull out of synchronism. Generator No. 1 increased in speed until it tripped the emergency overspeed governor at 1,960 rev. per min., shutting off all steam input to the turbine The turbine then drifted down to normal speed and pulled into step with the system 5½ seconds after the short circuit occurred.

There was very little reduction in steam input to the turbine until the emergency overspeed governor operated and closed both the throttle and intercepting valves. This was due to the stored energy in the reheat boilers and piping, and would not be true for an ordinary single-cylinder, non-reheat type of turbine. The results obtained from this test were exactly analagous to those previously experienced during lightning storm conditions. The indicating meters on the control board swung violently during the first one or two seconds of the disturbance, and again as the machine pulled into synchronism. During the intermediate time, the slip frequency was so high that the indicating instruments could not follow the changes. The entire disturbance was over in six seconds with nothing to indicate to the operator, except the tripped emergency overspeed governor, that the turbine had been out of step with the system.

A graphic voltage recorder with high-speed feature is normally used to record transient disturbances on this 66-kv. bus. The chart obtained from this instrument during this test is shown in Fig. 7A. Fig. 7B was obtained during a lightning storm when the emergency overspeed governor operated. The exact similarity of these charts indicates that the conditions existing during this test must have closely approximated those experienced during the storm disturbances. The voltage chart obtained from the graphic recorder should also be compared with the voltage chart shown in Fig. 8, which was taken during this test by means of a high-speed photographic recorder. This later type of instrument gives a true picture of the voltage conditions and the comparison illustrates the limitations of graphic instruments as recorders of fast transient phenomena. Another chart which was taken during test No. 34 by this graphic instrument is shown in Fig. 7E. This chart indicates a bad voltage disturbance followed by a period of low, slightly fluctuating voltage. Actually, the generator was out of step with the system, and voltage variations were about the same as shown in Fig. 8 obtained by the photographic recorder. Considerable caution must therefore be used in interpreting system disturbances from such graphic charts.

Test No. 13. Calculations had indicated that generator No. 1 would be stable with loads up to 25,000 kw., and a two-conductor-to-ground short circuit duration of less than ¾ second. A two-conductor-to-ground short circuit was thrown on the system with a 25,000 kw. load on generator No. 1, but due to the relay setting which kept the short circuit on for 1.7 seconds,

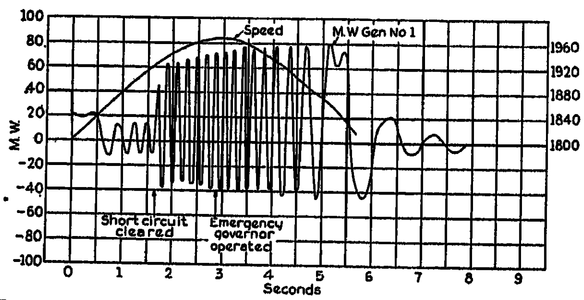
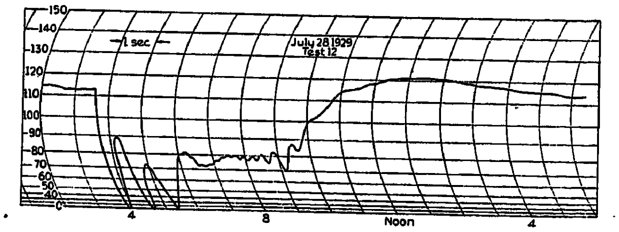


Fig. 6—Test 12. Two-Conductor-to-Ground Fault. Generator No. 1 Unstable, Generator No. 2 Stable

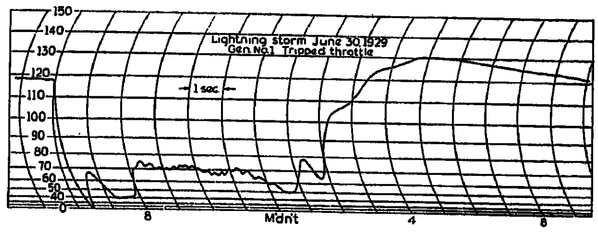
the generator again went out of synchronism but did not trip the emergency overspeed governor. Generator No. 2 being heavily loaded, 43,000 kw., lost synchronism with the rest of the system and tripped the emergency overspeed governor. Violent oscillation of the governor beam of generator No. 1 occurred before it resynchronized, but unfortunately, the oscillograph films had run through before this oscillation took place and no record of it was obtained.

Test No. 14. The relay setting was changed to reduce the short circuit time to 0.65 seconds and the

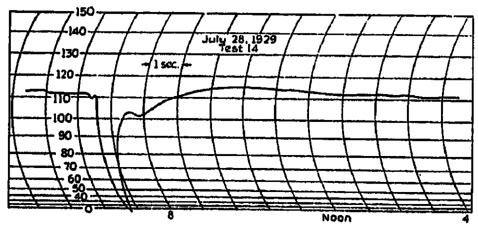


A. Voltage on Scranton Electric Co. 66-kv. bus at Scranton obtained by graphic recorder

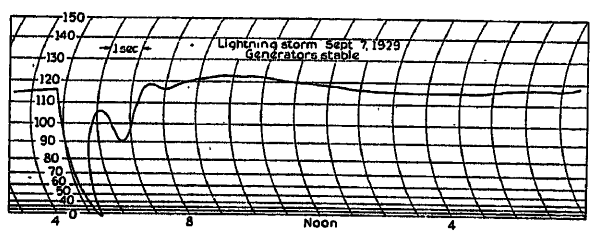
Test 12, Generator No. 1 unstable
Generator No. 2 stable



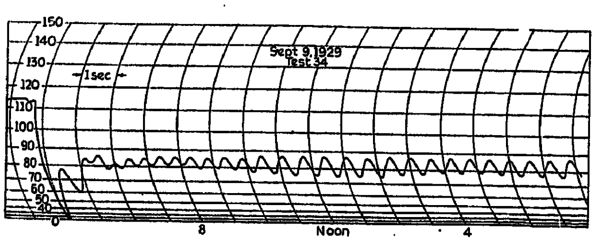
B. Lightning storm
Generator No. 1 unstable
Generator No. 2 stable



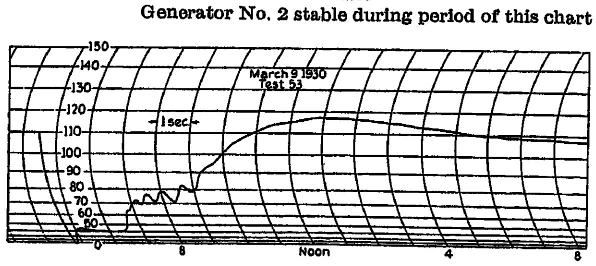
C. Test 14—Both generators stable



D. Lightning storm. Both generators stable



E. Test 34, Generator No. 1 unstable
Generator No. 2 stable during period of this chart



F. Test 53, Generator No. 1 unstable
Generator No. 2 stable

FIG. 7

short-circuit test was repeated. Fig. 9 shows the resultant kilowatt swing of generator No. 1. The system was stable and there was very little movement

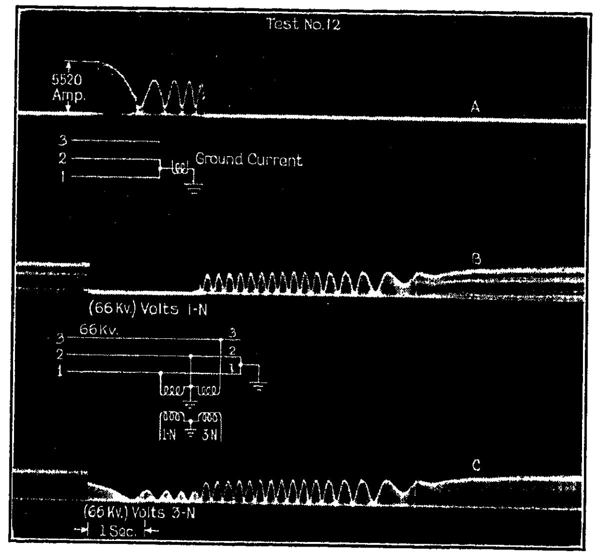


FIG. 8—TEST 12. GROUND CURRENT AND VOLTAGE ON SCRANTON ELECTRIC CO.

66-kv. bus at Scranton obtained by high-speed photographic recorder. Compare B and C with Fig. 7A

A—Fault ground current
B—Voltage phase 1-N 66-kv. bus
C—Voltage phase 3-N 66-kv. bus

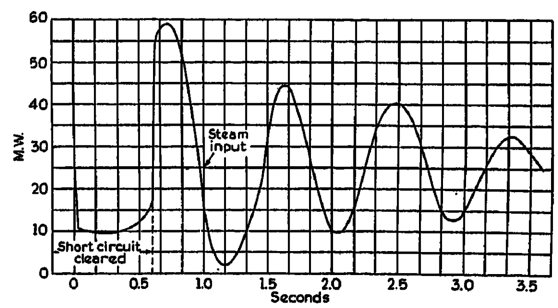


FIG. 9—TEST 14. BOTH GENERATORS STABLE

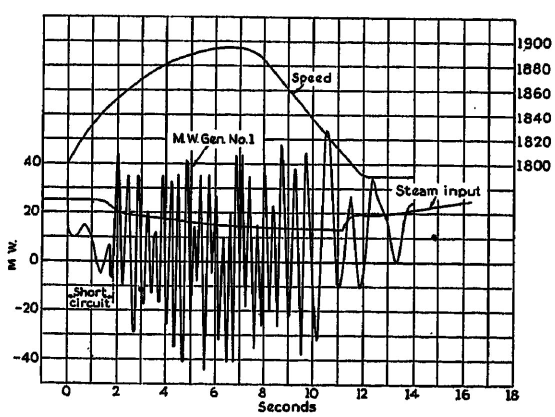


FIG. 10—TEST 23. BOTH GENERATORS UNSTABLE, OUT OF SYNCHRONISM WITH THE SYSTEM AND WITH EACH OTHER

of the governor beam, consequently, no change in the steam input to the turbine. Fig. 7C shows the graphic voltmeter chart made during this test and Fig.

7D a very similar chart obtained during a lightning storm. These last two tests illustrate the value of fast clearing of the short circuit.

Test No. 23. After obtaining longer films for the oscillographs, another test was made under the same load and short-circuit conditions as in Test No. 13. Fig. 10 for this test shows that both generators were out of synchronism not only with the system but also with each other. This is evidenced by the uneven peaks in the curve showing the kilowatt output of generator No. 1.

From this group of tests it is evident that generators lose synchronism for a brief time and then pull back into step again without giving evidence of this change, except by the magnitude of the disturbance; and also that system disturbances sustained after short circuits have been cleared are caused by loss of synchronism.

Part II

Governor Pumping

Load Transfer Tests. Several operating companies have reported that during certain system disturbances the governor beams of their turbines have oscillated, and that this oscillation has continued for 2 or 3 minutes, or until some means was taken to correct the condition, such as holding the governor beam, or disconnecting the turbine from the system. This phenomenon has generally been termed "governor pumping" and should not be confused with governor hunting which is a slow periodic movement caused by lag of the valve behind the governor.

Inasmuch as very little adequate data were available on governor pumping and due to the fact that it had appeared in test No. 13, it seemed advisable to attempt its reproduction for the purpose of recording and analyzing this disturbance.

Load transfer tests were first made to determine if governor pumping could be produced by a disturbance of a minor magnitude. In these tests the 66-kv. tie from Suburban to Wallenpaupack was opened leaving the Scranton Electric system entirely free from the other system except for the 66-kv. tie through the bus reactor at Stanton. The first tests were made by operating generators Nos. 1 and 2 at various loads so that initially power was transferred across the 66-kv. bus tie. With this arrangement, by opening the bus tie breaker it was possible to suddenly increase or decrease the load on generator No. 1 as much as 20,000 kw., but it was impossible with any of these load transfer tests to obtain any sort of sustained oscillation.

Next, a test was made to see if it were possible to start a sustained oscillation by suddenly disconnecting the generators from all loads but not from each other when they were carrying unequal portions of the load. Generator No. 1 was loaded to 30,500 kw. and No. 2 to 10,000 kw., and then the oil circuit breaker to the load was tripped. Generator No. 1 dropped to 5,000 kw. load as a generator and No. 2 took 5,000 kw. as a motor; the two generators increased in speed until they tripped the emergency overspeed governors. No oscillation of any magnitude was obtained either in the kilowatt output of the generators or in the movement of the governor beams.

In another test the governor beam was slowly pressed down until the load on generator No. 1 was reduced from 40,000 kw. to 22,000 kw. The governor beam was then released and the generator picked up its previous load of 40,000 kw. without any appreciable oscillation of governor beam or kilowatt output.

From this series of tests, it was concluded that it would be impossible to set up a sustained oscillation in the governor equipment without a much more severe system disturbance. Therefore, two-conductor-to-ground short circuits were then made in an effort to reproduce the pumping previously noted in test No. 13. While these tests were successful in reproducing the phenomenon, the best record was obtained in testing the special turbine valve equipment discussed in Part III. The records from test No. 34 are therefore used as a basis for the following analysis of governor pumping.

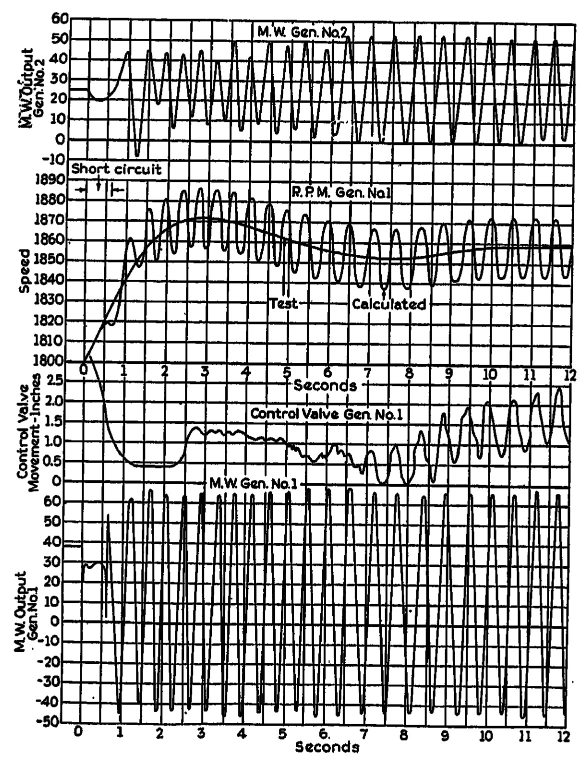


Fig. 11—Test 34. Pumping of Governor and Control Valve

Test No. 34. This was a two-conductor-to-ground short circuit test in which the generator lost synchronism but did not trip the emergency overspeed governor so that the speed governor still controlled the steam input. The reduction in the generator output due to the loss in synchronism coupled with the normal speed regulating characteristics of the governor resulted in a sustained prime mover speed above that of the system.

Fig. 11 shows the results of this test. During the

first 2.5 seconds the movement of the main control valve was controlled by an auxiliary pilot valve which was being used in a preliminary form in an attempt to keep the turbine in synchronism; this pilot valve, however, had no effect on the governor or control valve after this initial period. Seven seconds after the short circuit occurred the governor mechanism started to oscillate at a period coinciding exactly with the kilowatt oscillation of the generator. The speed curve shown is a

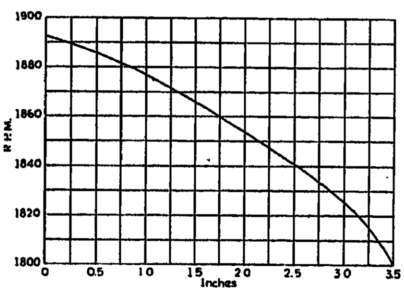


Fig. 12—Test 34. Control Valve Position Versus Turbine Speed

composite curve, composed of an average speed curve obtained from the oscillograph record, and a superimposed speed change calculated from the output of the generator and added to the average speed curve. From this composite curve it can be seen that if the governor follows the speed of the turbine it must alternately open and close the control valve an appreciable amount. The curves show that the governor was doing its best to follow these speed changes, although with about a quarter second time lag, and was thus varying the steam input in accordance with the speed, which is exactly what a speed governor is designed to do.

Fig. 12 shows the relation between speed and control valve position for this particular test. About 8 seconds after the occurrence of the short circuit, the speed of the turbine was approximately 1,860 rev. per min. with a periodic plus and minus speed variation of 15 rev. per min. This 30 rev. per min. speed change at the average speed of 1,860 rev. per min. calls for a control valve stroke of about 1.3 in. Reference to Fig. 11 shows that the stroke of the control valve at this time was about 1.3 in. and the average position was about correct for the average speed.

During the interval from the third to the seventh second, the periodic speed change caused by the generator slipping poles was so fast that it was impossible for the control valve to follow it. However, as soon as the average turbine speed came down to a point where the governor mechanism and control valve could follow the periodic changes in speed, the control valve started a pumping movement in which it assumed the proper position corresponding to the speed. This pumping of the governor beam was therefore a normal action and should be expected under conditions such as existed at the time of its occurrence.

Fig. 13 shows the speed regulation curve for the governor of this turbine at the load carried when this test was made. If the turbine was completely unloaded it would run about 5 per cent above the normal system speed. The figure also includes a curve showing the relation between speed of the turbine and the induction generator output of the generator for the voltage conditions which existed on this system during this test. The point where the induction generator curve crosses the speed regulation curve determines the speed of the turbine and the load which it will carry when it is out of synchronism. The average output of the generator during the period covered by the curves was about 13,000 kw. and the speed was about 3.3 per cent above normal.

Due to the steam storage in the reheat boilers on this particular type of turbine, the oscillation of the main control valve had very little pulsating effect on the steam energy input to the turbine. This was evidenced by practically constant steam input pressure obtained on a pressure recorder at the eighth stage where steam is admitted to the turbine from the reheat boilers.

During the period that the governor beam was oscillating in synchronism with the kilowatt oscillation of the generator, the speed of the generator was about 1.8 cycles above the speed of the system. This represents a slip frequency of 108 cycles per minute. The natural period of oscillation of the governor weights and springs, without the frictional resistance of the pilot valve and oil system, is about 200 cycles per minute. Due to this difference in natural period of oscillation, it seems reasonably sure that the governor mechanism itself contributed nothing to the oscillation of the governor beam and control valve. The speed change must

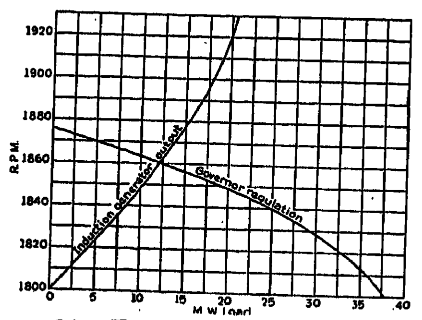


Fig. 13—Test 34. Turbine Regulation and Induction Generator Power

at least be considered the primary cause of the oscillation or pumping.

An effort was made to stop the pumping of the governor beam by steadying it by hand; the oscillation itself was damped by this means, but the turbine did not slow down and resynchronize due to the fact that no reduction was made in steam admission. The turbine was finally pulled into synchronism with the system when the main throttle valve was closed by hand, allowing the turbine to come down in speed. Considerable oscillation had been noticed in the meantime

on generator No. 2 and it was removed from the system by tripping the generator oil circuit breaker.

There are two ways of curing this governor pumping after it has once been started. The first method, which may be preferred in many instances, is to reduce the speed of the turbine so that it will synchronize with the rest of the system. The second method is to remove the generator from the system by tripping the generator oil circuit breaker. The operator in the switchboard gallery can apply the first method by operating the synchronizing motor on the governor spring, and the second method by tripping the generator oil circuit breaker. The turbine man can also apply the first method by tripping the throttle valve. This valve, however, should be reopened the instant the generator pulls into synchronism to avoid burning the turbine blades. As the turbine speed will decrease rapidly when the throttle valve is closed the generator will usually resynchronize by the time the turbine man is ready to reopen this valve.

Previous investigations of this peculiar governor pumping have shown that it was apparently possible to damp out such an oscillation during some tests by merely introducing frictional resistance on the governor beam, but during other tests this frictional resistance method was not successful. In all previous investigations it has only been possible to set up governor pumping by some very severe system disturbance, which in all probability meant that the generator was out of synchronism with the rest of the system. The results of these previous investigations also suggest that the primary cause of such governor pumping is loss of synchronism and consequent periodic speed change of the generator involved as it slips poles as found in the tests made at Stanton.

If the regulation of the turbine governor from no load to full load is small the slip frequency when the generator is out of step will be low, consequently a relatively long time is available to alternately store and take energy from the rotor. This will result in a large periodic change in speed at a low frequency which can be easily followed by the governor, and will cause the control valve to move over a wide range. If the regulation is increased the speed at which the turbine will run when out of synchronism will be higher, the slip-frequency between the generator and the rest of the system will be greater, and the speed change as the generator slips poles will be less. All of these factors tend to reduce the effect on the governor and make it more difficult for it to follow the periodic speed changes due to pole slipping. This may explain why it has apparently been possible to cure some cases of governor pumping by merely broadening the regulation range of the governor.

Reducing the field of the generator as has been done in some previous tests, would also tend to reduce the magnitude of the periodic speed change as the generator slips poles, and consequently reduce the effect on the governor.

From this series of tests the following facts seem to be evident:

1. The turbine governors operate correctly under all normal conditions of load transfer and system disturbances as long as the generators remain in step with the rest of the system.

2. Pumping of the governor mechanism occurs primarily because of a periodic change in speed of the turbine.

3. Pumping of the governor mechanism may continue indefinitely if the generator loses synchronism and the steam input is not cut off.

4. Pumping will terminate if the generator is synchronized with, or segregated from, the system. Synchronization may be expedited by cutting off the steam input to the turbine so that its speed will be reduced and again match that of the system.

Part III

Tests with Special Valve Equipment

In the previous short-circuit tests, all really severe system disturbances were accompanied by a loss of synchronism of one or both of the generators. When the generator lost synchronism under light load conditions and did not trip the emergency overspeed governor, considerable oscillation, or pumping, of the governor beam was noted To prevent both the severe system disturbances and the pumping of the governor beam, it was evidently necessary to keep the generator in synchronism with the rest of the system. One solution of the problem was, of course, to reduce the short-circuit time as shown by Tests Nos. 13 and 14. However, it was quite doubtful that sufficient decrease in short-circuit time could be secured and selective relaying also maintained with existing system connections and equipment. Therefore, the possibility of holding this turbine in synchronism by rapid reduction of input steam following a system disturbance seemed in this case to justify investigation. A special power surge relay and a valve mechanism were therefore designed to shut off the steam input to the turbine by closing the main control and intercepting valves temporarily when a short circuit occurred.

The power surge relay was a three-phase wattmeter element arranged with a normally open pair of contacts which would not close for a slow change in power output of the alternator, but for a sudden decrease in the output would close quickly and then remain closed for a time proportional to the magnitude and duration of the power change. This measure of the reduction in the kilowatt output of the turbine determined the time that the steam valves of the turbine remained closed, and thereby reduced the steam input in proportion to the reduction in the output. The valves were then allowed to reopen and the turbine to resume the same load that it was carrying before the disturbance.

In order to obtain a fast reduction in steam input to the turbine it was necessary to operate both the control valve and the intercepting valve on the reheat loop. The control valve with its oil operating cylinder and pilot valve was not changed as it was found that the closing time of this valve was short enough to give the desired results due to the fact that there was only about 25 per cent of the total turbine output under control of this valve during the first two seconds. A solenoid operated valve was added to the pilot valve to permit its control by the power surge relay. This arrangement also provided for the necessary free control of the pilot valve by the operating governor under normal load conditions.

The intercepting valve on the reheat loop, however, was found to operate too slowly. This necessitated a new valve cylinder with larger ports, and a stronger operating spring. A separate trip valve was installed, large enough to insure dumping of the operating cylinder oil in the required time. This trip valve was also oil operated through a solenoid operated pilot valve. As originally designed the intercepting valve was given a long stroke to insure a small pressure drop through it, but while making these tests this stroke was reduced so that the steam flow was restricted as soon as the valve started to close. In this manner a closing time of about ¼ second was obtained for these valves.

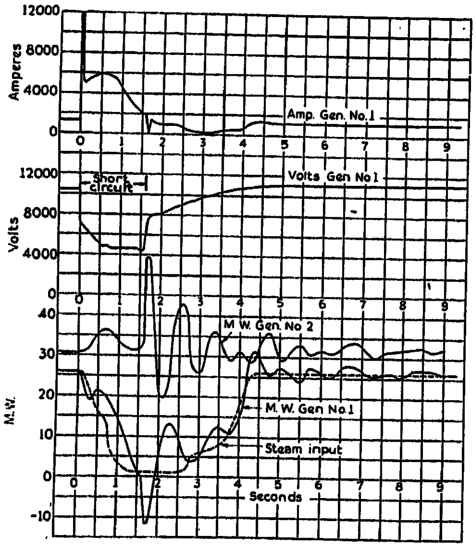


Fig. 14—Test 51. Special Valve Equipment. Both Generators Stable

Tests of the special valve equipment prior to these changes did not give the desired increase in stability due to the slow closing of the intercepting valve.

Test No. 51. Tests Nos. 14 and 23, the results of which are shown in Figs. 9 and 10, respectively, were two short circuits with similar load conditions on the turbine, but with a different duration of the short circuit. These tests were made with standard governor control equipment. In Test No. 23 both generators No. 1 and No. 2 lost synchronism with each other and with the rest of the system.

Fig. 14 (Test 51) shows the results of a two-conductor-to-ground short circuit on the 66-kv. bus with the kilowatt load on generator No. 1 the same as for Tests Nos. 14 and 23, and the short-circuit time the same as for Test No. 23. The load on generator No. 2 was, however, somewhat reduced from its previous load. The steam input curve on this figure shows how the high-speed valve mechanisms used in this test, but not in Tests Nos. 14 and 23, reduced the input so that the generator not only did not lose synchronism with the rest of the system, but even drifted back in angle so fast that it was taking power as a motor when the short circuit cleared.

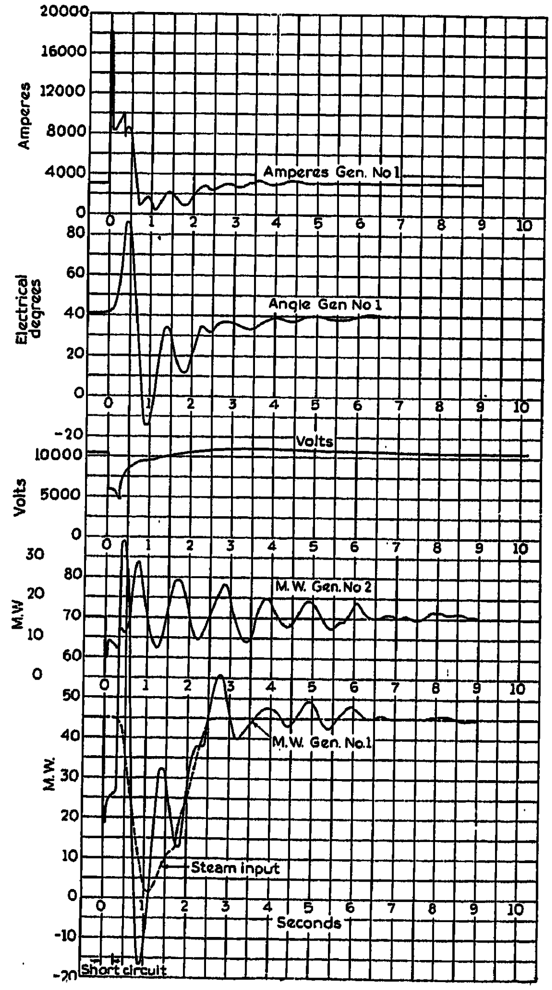


Fig. 15—Test 52. Special Valve Equipment. Both Generators Stable

Test No. 52. Another short-circuit test was then made with full kilowatt output from generator No. 1, but with the relay set so that the oil circuit breaker opened the short circuit in 0.33 seconds. Fig. 15 shows the results of this test. Note that the generator did not pull out of synchronism.

Test No. 53. In order to see if the equipment would

hold the generator in synchronism irrespective of the duration of the short circuit, another test was made with full load on generator No. 1, but with the relay adjusted so that it cleared the short circuit in 1.78 seconds. The results of this test are shown in Fig. 16. The steam input for generator No. 1 is not available on account of faulty operation of some of the recording devices. Generator No. 1 pulled out of synchronism with the rest of the system, and after slipping 16 poles, pulled back into step again. A special asynchronous relay had been included in the test equipment so that if the generator did lose synchronism the steam valves of the turbine would be kept closed for 7 seconds before

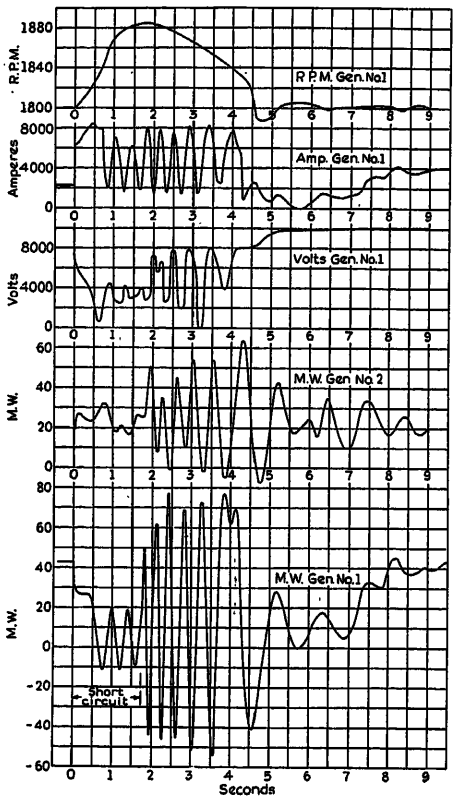


FIG. 16—TEST 53. SPECIAL VALVE EQUIPMENT

Generator No. 1 unstable
Generator No. 2 stable

they would reopen and enable the turbine to resume its full load.

Although generator No. 1 pulled out of synchronism with the system during this test, it is felt that by a few further refinements in the relay and valve mechanism, it would be possible to keep this generator in synchronism with the rest of the system even for short circuits as severe as in this test.

These tests evidence the possibilities of this method for improving system stability and indicate results which are comparable with those obtained by the use of the more commonly proposed means for attaining the same end.

It should be borne in mind that the application of this scheme to certain complex types of turbines can not always be economically justified owing to the large amount of supplementary control equipment required, and the unreliable operation which may ensue.

TABLE I
SUMMARY OF TESTS

Test No.	Initial load in mw. Gen No. 1	Initial load in mw. Gen. No. 2	Duration of short circuit cycles	Valve control	Stability of system	Fig. No.	Remarks
11	38	30	100	Standard	Stable	5	1 C. G. Fault
12	40	31	100	Standard	Unstable	6, 7, 8	2 C. G. Fault
13	25	43	100	Standard	Unstable		2 C. G. Fault
14	25	43	39	Standard	Stable	9	2 C. G. Fault
20	35	43	..	Standard	..	20	Load Transfer Test
23	25	43	100	Standard	Unstable	10	2 C. G. Fault
34	38	25	40	Semi-Special	Unstable	7, 11	2 C. G. Fault
50	35	20	..	Special	..	20	Load Transfer Test
51	25	31	98	Special	Stable	14	2 C. G. Fault
52	44	20	19½	Special	Stable	15	2 C. G. Fault
53	45	20	106	Special	Unstable	16	2 C. G. Fault

Part IV

MISCELLANEOUS TEST DATA AND GENERAL COMMENTS

Load Dropping Tests. A number of tests was made to determine the increase in speed of the turbine caused by the stored energy in the reheat boilers and piping. During these tests, all load on the house generator was removed so that the entire turbine load could be dropped by opening the main generator oil circuit breaker.

With the reheat boilers in service, a load of 32,000 kw. was dropped causing the turbine to overspeed and trip the emergency governor. With the reheat boilers out of service it was possible to drop 31,500 kw. without the turbine speed becoming high enough to trip the emergency governor; but when 36,500 kw. was dropped, the emergency governor tripped at 1,955 rev. per min. The turbine speed increased to a maximum of 1,965 rev. per min. during this test.

With the reheat boilers in service, one test was made by connecting the generators so that load was dropped from both generators, but the generators themselves were left connected together. Generators Nos. 1 and 2 initially carried 30,500 kw., and 10,000 kw. respectively. Generator No. 1 continued to operate as a generator, driving generator No. 2 as a motor, and under these conditions, the machines overspeeded together and tripped both emergency governors.

The standard governor was used in all these tests and it was found that the pilot and main control valves were very fast in following the movement of the governor beam. The pilot valve moved within 2 cycles and the main control valve within 4 cycles after the movement of the governor beam. The governor itself responded in two or three cycles to any change.

Load Transfer Tests. Of the many load transfer tests made on the Stanton turbines, two were of outstanding interest in showing the effectiveness of the

special valve equipment. In these tests, system connections were such that the initial 35,000 kw. output of Generator No. 1 was divided, 11,000 kw. being sent through a long tie line by the way of Wallenpaupack to the Pennsylvania Power & Light Company, and the remaining 24,000 kw. being supplied direct to the Scranton Electric Company. The Scranton Electric breaker was then opened, forcing the entire 35,000-kw. output over the Wallenpaupack tie line. The kv-a. loading of this tie line was limited to 18,000 kv-a. by

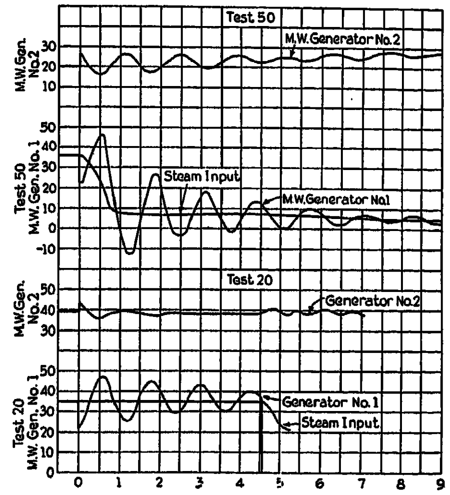


FIG. 17—TESTS 20 AND 50. POWER OVER LONG TIE LINE WITH AND WITHOUT SPECIAL VALVE EQUIPMENT

relays at Wallenpaupack. For Test No. 20, Fig. 17, the turbine was equipped with a standard governor. After the breaker controlling the Scranton Electric load was opened, the generator load oscillated about an average output of 35,000 kw., until the breaker at

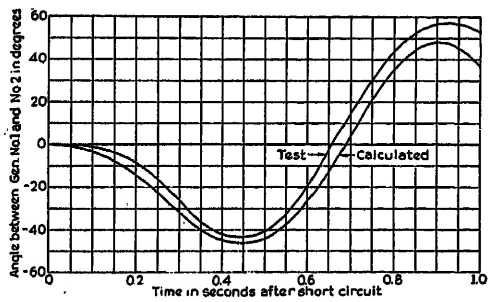


FIG. 18—TEST 52. COMPARISON OF TEST AND CALCULATED RELATIVE ANGLE BETWEEN GENERATORS NOS. 1 AND 2

Wallenpaupack tripped on overload. In Test No. 50 (Fig. 17), the same switching arrangements were used, but the turbine was equipped with special valve mechanism. In this test, the valves started to close as soon as the Scranton Electric breaker opened and the output of the generator was sufficiently reduced so that the breaker at Wallenpaupack did not open.

Damping. The data on the Scranton tests also gave some indication of the change in damping of the generators with different values of resistance in the armature circuit.

Fig. 9 shows the damping of generator No. 1 with small external armature resistance. The amplitude of the oscillations of the generator decreases quite rapidly and after a few swings dies out entirely. Fig. 17 shows the oscillations of the same generator with considerable

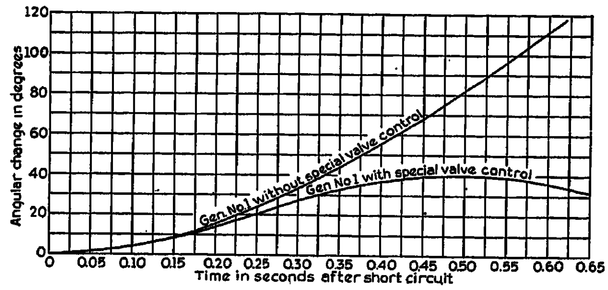


FIG. 19—CALCULATED SWING OF GENERATOR 1 DURING A TWO-CONDUCTOR-TO-GROUND FAULT WITH AND WITHOUT SPECIAL VALVE EQUIPMENT

external resistance in the armature circuit. The amplitude of the oscillations decreases quite slowly and indicates that under these conditions the generator damping was but slightly positive. These tests therefore indicate that damping in a synchronous machine decreases as the external armature resistance increases.

Comparison of Tests and Calculation. Many mathematical computations of system stability have been made but seldom has there been an opportunity to make actual checks on these calculations by applying short circuits to the system while it is in operation.

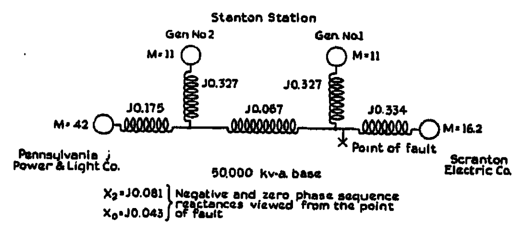


FIG. 20—EQUIVALENT REACTANCES AND INERTIA CONSTANTS OF THE SYSTEMS

It is, therefore, interesting to compare the values obtained from the tests with values calculated for the same conditions. Such a comparison is given in Fig. 18 which shows the relative angle between the two Stanton generators during a two-conductor-to-ground fault. It will be noted from this figure that the calculated curve has the same relative shape as the test curve and follows it quite closely, especially during the first swing of the generators.

Calculations were also made to determine the increase in stability to be expected with the special valve control mechanism. The curves shown in Fig. 19 show the angular change of generator No. 1 due to a two-conductor-to-ground fault with and without the special valve control equipment. These curves indicated that

generator No. 1 could be made to remain in synchronism with the system with the special valve control equipment. This was substantiated by test.

Effect of Voltage Regulators. The main generators have direct-connected, self-excited, 250-volt exciters. The rate of exciter voltage build up at the voltage required for full load on the generator is 80 volts per second. The exciters are equipped with rheostatic type regulators. Records were taken of the generator field voltage and current, and the voltage across the regulator contacts during some of the short-circuit tests. These records show that the regulator attempted to maintain maximum field on the exciter throughout the disturbance, and that about 2.5 seconds were required to raise the exciter voltage from 175 volts to the exciter ceiling of 275 volts. Due to this slow build up of the exciter voltage, it is evident that the regulator had very little effect during the time the short circuits were on the system.

ACKNOWLEDGMENT

The authors wish to express their appreciation of the cooperation of Messrs. C. H. McKnight and J. E. Geue of the Stanton Operating Company in the performance of these tests and arrangement of system operation with connecting companies. They also wish to acknowledge the assistance of Mr. R. H. Park who initiated the tests with the high-speed valve mechanism, Mr. J. W. Dodge for assistance in the preparation of the test results and Mr. D. M. Jones for criticism of the paper.

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Appendix A

DESCRIPTION OF SYSTEM, STATION, AND TEST EQUIPMENT

Description of System. The Scranton Electric Company and the Pennsylvania Power & Light Company serve a considerable portion of eastern Pennsylvania. The Scranton Electric Company supplies power to the section in and around the city of Scranton. This is normally received from the Stanton Plant, and distributed over the 66-kv. and 22-kv. networks. The Suburban Plant is located in the city of Scranton, and has an installed capacity of approximately 70,000 kv-a. This plant is not normally in operation, but was used during these tests to insure continuity of load supply. The 22-kv. network is normally fed through a 30,000-kv-a. transformer bank located at Suburban.

The Pennsylvania Power & Light Company serves the section around Wilkes Barre, west as far as the Northumberland district, south as far as Harrisburg, and east to the Allentown district. The main generating plants are Wallenpaupack, 40,000 kw., Hauto 55,000 kw. and Pine Grove 55,000 kw. The transmission system is composed chiefly of 66-kv. lines.

Fig. 2 shows the main transmission network of the two systems, unimportant portions shown only as equivalent networks, with the generating capacity and reactance of all lines and apparatus. The reactance values are all on a 50,000-kv-a. base. These two systems have two interconnections, one, through a 66-kv. bus tie reactor at the Stanton Plant, and the other through a 66-kv. line extending from Peckville (Scranton Electric Company) to the Wallenpaupack Plant of the Pennsylvania Power & Light Company. The line distance from Stanton to Wallenpaupack is 44 miles; from Stanton to Siegfried, 37 miles; and the tie from Wallenpaupack to Siegfried is made by a 64-mile, 220-kv. line.

The Pennsylvania Power & Light Company has a low reactance tie to the Philadelphia Electric Company by means of a 220-kv. line from Siegfried to Plymouth Meeting. It also has 66-kv. ties with the Luzerne County Gas and Electric Company at Stanton, Wilkes Barre, and Berwick. This latter company has generating plants indirectly tied to Harwood with a total capacity of approximately 50,000 kw.

Because of the bus tie reactor between the systems at the Stanton Plant and the 32-mile, high reactance line from Scranton to Wallenpaupack, there was a tendency for generator No. 1 and the Scranton system to swing as a unit during transient disturbances. Due to the fairly heavy network of the Pennsylvania Power & Light Company, and the low reactance tie from Siegfried to Wallenpaupack and Plymouth Meeting, this part of the interconnected system also tends to swing as a unit under transient conditions.

Station Equipment. Fig. 3 is a one line diagram of the Stanton Station showing the main electrical connections. The high-voltage bus scheme is employed, that is, the generator and transformer are operated as a unit, no switching being done on the low-voltage side of the transformer bank. The station auxiliaries are normally fed from each house generator although it is possible to feed them from a transformer connected

to the 66-kv. bus on the Scranton Electric side of the station.

The two main generators are each rated 52,630 kv-a. 0.92 power factor, three-phase, 60 cycle, 11,000 volts. Generator No. 1 normally supplies power to the Scranton Electric Company, and No. 2 to the Pennsylvania Power & Light Company. Power is generated at 11,000 volts and transmitted at 66,000 volts. The two systems are separated at the plant by a 7 per cent bus tie reactor connecting the two 66-kv. buses.

Each turbine shaft also carries a 3,283-kv-a. 0.7 power factor, three-phase, 60-cycle, 2,300-volt house generator, and exciters for the main and house generators. The exciter for the main unit is a shunt wound machine rated 250 kw. at 250 volts; its voltage is controlled by a rheostatic type voltage regulator. The main step-up transformers are each rated 52,500 kv-a., and are solidly grounded on the 66-kv. side. The 66-kv. bus arrangement is practically identical on both the Pennsylvania Power & Light Company, and the Scranton Electric Company's side of the station. The switching scheme consists of a main and reserve bus having a circuit breaker selector scheme.

The 66-kv. reactor connecting the two buses formed a part of the ultimate station plan in which it was necessary to limit the breaker duty by use of reactors. It was also felt that in the present initial installation that the reactor would limit somewhat the magnitude of voltage troubles that might be reflected from one system into the other.

The relaying for the outgoing lines from this station is provided by balanced current or balanced power protection where parallel lines are involved, and straight over-current protection for single circuit lines.

The steam turbines are rated 50,000 kw., 1,800 rev. per min., 19 stages with initial steam pressure of 600 lb. per sq. in., and temperature of 725 degrees. The steam is reheated between the 7th and 8th stages to 725 degrees.

Steam extractions are provided for feed water heating from the 12th and 16th stages; additional extraction from the 6th stage is used for operating the air jet for the condenser when this pressure is over 100 lb. per sq. in., or about 20,000 kw. load on the turbine. The reheat system is shown diagrammatically on Fig. 1, and consists of a 20-in. diameter line from the 7th stage outlet to the reheaters and a 24 in. diameter line from the reheaters to the 8th stage admission. The reheater is by-passed by shutting the valves in the lines to and from the reheater, and opening the by-pass valve located at the turbine.

There is approximately 25 per cent of the total turbine power generated in the high-pressure section, and 75 per cent in the low-pressure section. At ful lload the reheater and connections contain approximately 270 lb. of steam, while the turbine flow is approximately 100 lb. per second. This gives, therefore, a large reservoir of energy for the low-pressure section of the turbine.

The turbines are designed for base load, with a single control valve connected through a relay system to the operating governor. There is also an intercepting valve in the reheat steam line at the inlet to the 8th stage of the turbine. This intercepting valve as well as the control valve and turbine throttle valve are under the control of the emergency governor which operates about 10 per cent above normal speed. The movement of the control valve, intercepting valve, and turbine throttle valve in response to the governors is accomplished by oil pressure. The control valve follows the operating governor movement by means of a pilot valve; return motion from the control valve recenters the pilot valve, so that the control valve takes a definite position for each position of the operating governor. The intercepting valve and throttle valve, having no return motion, are either open or shut. These valves are shut by relieving the oil pressure in the valve operating cylinders.

Test Equipment. In order to obtain simultaneous records of all the varying elements during a disturbance, it was necessary to use six oscillographs with a total of 22 vibrators. One element of each oscillograph was used as a timing wave. This wave was interrupted every second, so that it was possible to line up all the films after the test, and obtain the proper sequence of events. Preliminary tests with films five feet long did not give sufficient time to obtain a complete record of all the disturbances. Films 15 ft. long were obtained for the remainder of the tests. These were run at a speed of about one ft. per sec.

Two three-phase wattmeter elements were used to measure the kilowatt output of the two generators in the station. Current and voltage were measured during all tests involving short circuits; voltage from the 66-kv. buses to ground was obtained during some of the tests by means of two photographic, high-speed recorders.

The recording of the mechanical measurements on the oscillograph films raised several unique problems. Records of the pressure at several points in the hydraulic system of the turbine governor equipment, and of the steam pressure at the 8th stage of the turbine, were obtained by means of pressure recorders which had been developed for testing pressure in oil circuit breaker tanks during short-circuit tests. These recorders consist of a small solenoid coil in a magnetic frame with a flexible steel diaphram. The pressure applied to this diaphram varies the air gap in the magnetic circuit of the coil. A 500-cycle a-c. voltage is impressed on the coil, and the resultant current which changes with the pressure can be recorded by an oscillograph.

It was desired to record the movement of the governor beam very accurately. Contact resistance devices were tried during the first tests, but were unsatisfactory due to the force necessary to move the device and the space necessary between the contacts. Finally a special photoelectric cell position indicating device

was designed and used for the latter portion of the tests. This device consisted of a small disk with unequal holes around its periphery. The light was arranged to shine through these holes on a photoelectric cell; the change in the resistance of the photoelectric cell was used to operate an amplifying tube, the output current of which was recorded by the oscillograph. Each time a hole in the disk admitted light to the photoelectric cell, a deflection of definite magnitude was obtained on the oscillograph. This disk was fastened to the governor beam by means of a steel wire so that any movement of the governor beam would rotate the disk. By means of this device it was possible to measure the movement of the governor beam to 0.01 in. over its total travel of 4 in. The movement of the main control valve and intercepting valve was recorded satisfactorily by means of a contact resistance device.

To obtain the average speed of a turbine, a small synchronous converter was equipped with a large flywheel and run from the direct current end. The a-c. voltage of the converter was compared with one phase voltage of the house generator of the turbine by connecting the oscillograph so that it would read the vector difference of the two voltages. Before each test the converter was adjusted to the same speed as the turbine, so that the vector difference of the two voltages was about constant. The change in this vector difference during the test was used to obtain the speed of the turbine. The house generators on the two turbines are arranged on the shaft so that they have the same phase relation. The relative angular movement of the two turbines was recorded by taking the vector difference of like phases of the two house generators.

Appendix B

Calculation of Stability Limits and Short-Circuit Current

To study the electrical system stability, the system reactances were reduced to an equivalent four machine system; the two machines at Stanton were considered as generators tied together through the bus tie reactor, and equivalent motors represented the Pennsylvania Power & Light Company system and the Scranton Electric Company system. One- and two-conductor to ground faults were considered outside of the generator No. 1 high-tension bus as shown in Fig. 20. The positive, negative, and zero phase sequence reactances viewed from the point of fault together with the inertia constants for these machines are also shown in this figure.

Before making the tests at the Stanton Station, calculations were made to determine the stability limits of the system under short-circuit conditions and the short-circuit currents to be expected. For the preliminary calculations, the system was considered as a two machine problem; that is, the Stanton generator No. 1 was assumed to supply power to the rest of the system represented as an equivalent motor. The results of these calculations are shown in curve form in Fig. 4. With a one-conductor-to-ground fault, the stability limit was far above the rated kilowatt output of the generator, while the stability limit for a two-conductor-to-ground fault was approximately 25,000 kw. for a switching time of not more than three-quarters of a second.

Due to the low reactance tie between the generators in the Stanton Station, there was some doubt if reducing the system to a two machine problem could be justified. Close checks on these stability limits were made considering the Pennsylvania Power and Light Company and Scranton Electric Company systems as motors being supplied by the two Stanton generators as shown in Fig. 20, that is, swing curves were made for a four machine problem.

The real check on these calculations came when short circuits consisting of one and two conductors to ground were put on the system. As predicted by the calculations, the short-circuit tests showed that the system was stable with a one-conductor-to-ground fault but with a two-conductor-to-ground fault and a load of 40,000 kw. the system was decidedly unstable; but with a load of 25,000 kw. and short switching time, the system was stable. These tests are described in detail in the group from Test No. 11 to Test No. 14.

The short-circuit current calculated and checked by the oscillographs during a two-conductor-to-ground fault, was approximately 7,000 amperes in the ground with a corresponding 5,700 amperes in the faulty phases.

Appendix C

Change in Speed of a Rotating Body for a Given Energy Differential*

The formulas derived below were found to be quite useful in calculating a speed change for a given energy differential.

The fundamental equation for rotor motion is given by the equation

$$T = M \frac{d\,\omega}{d\,t} \tag{1}$$

where the per unit torque (T) is equal to some inertia constant (M) multiplied by the time rate of change of per-unit speed. The inertia constant (M) may be defined as the time required for the rotor to come to rest with unit decelerating torque applied at normal speed and maintained constant until zero speed is reached.

To evaluate (M), formula (1) is integrated from $\omega = 1$ to $\omega = 0$ with $T = -1$.

$$t = -M \int_1^0 d\,\omega = -M\,\omega \Big]_1^0 = M \tag{2}$$

Thus M is the time to come to rest with unit retarding torque applied.

*By Mr. I. H. Summers.

The energy differential is given by

$$\Delta E = \int_{t}^{t+\Delta t} T\,\omega\,d\,t = \int_{\omega}^{\omega+\Delta\omega} M\,\omega\,d\,\omega \qquad (3)$$

Where ΔE is the differential energy divided by the base power. This may be written

$$\frac{\Delta E}{M} = \int_{\omega}^{\omega+\Delta\omega} \omega\,d\,\omega = \frac{1}{2}(\Delta\,\omega)^2 + \omega\,(\Delta\,\omega) \qquad (4)$$

The quantity $\frac{\Delta E}{M}$ may be thought of as the differential energy divided by twice the rotor stored energy at normal speed.

The expression for the change in speed is

$$\Delta\,\omega = \sqrt{\omega^2 + 2\frac{\Delta E}{M}} - \omega \qquad (5)$$

Several modifications of the formula for $\Delta\,\omega$ have been found useful.

Starting from zero speed $\omega = 0$ and

$$\Delta\,\omega = \sqrt{2\frac{\Delta E}{M}} \qquad (5a)$$

Starting from unity speed

$$\Delta\,\omega = \sqrt{1 + 2\frac{\Delta E}{M}} - 1 \qquad (5b)$$

or starting from unity speed if $\frac{\Delta E}{M}$ is small there is approximately

$$\Delta\,\omega = \frac{\Delta E}{M} - \frac{1}{2}\left(\frac{\Delta E}{M}\right)^2 + \frac{1}{2}\left(\frac{\Delta E}{M}\right)^3 \qquad (5c)$$

To illustrate the use of formula (5c), a numerical example is given. The energy differential for one of the swings of the rotor during test 34 was 9,230 kw. sec. The constants for this machine are, $M = 11$, base power $= 50{,}000$ kw., normal speed 1,800 rev. per min. Then the speed change is

$$\Delta\,\omega = \left[\frac{\frac{9230}{50{,}000}}{11} - \frac{1}{2}\left(\frac{\frac{9230}{50{,}000}}{11}\right)^2 + \ldots\right] \times 1800$$

$$= 30 \text{ rev. per min.} \qquad (6)$$

Discussion

T. E. Purcell: These tests were made with about the same objective as those conducted under the writer's supervision several years ago and reported in a paper* presented at the winter convention of 1930. It is gratifying to learn that, in general, the results of these tests, although conducted under different conditions and in a different manner, are almost identical with results we obtained.

I am greatly surprised to learn from this paper that the turbines under test, overspeeded enough to trip the emergency governors when loads in excess of 60 per cent of the rated capacity were dropped and I am also surprised at the endeavor of the authors to point out that the correction of this most undesirable performance is a rather complex problem.

Trouble of this kind, that is machines tripping emergency governors due to loss of load, was encountered on the Duquesne Light Company's system, principally at the Colfax Power Station, for several years, until in 1925 the writer in cooperation with engineers of the Westinghouse Electric and Manufacturing Company agreed that this difficulty could be eliminated and diligently set about the task. The results of this work are outlined in a paper entitled "Load Dump Tests Made on Colfax Turbines" by the writer, which appeared in *Power* in 1929.

This feature of turbo generators, that is loss of load without tripping of emergency governors, is considered so important by us that it is one of the acceptance tests we conduct upon all new turbines installed. We have conducted tests upon a 60,000-kw. single-cylinder Westinghouse turbine, recently placed in service at our James H. Reed Power Station. The maximum load, about 70,000 kw., can be suddenly dropped by opening the generator oil circuit breaker without the emergency governor tripping.

E. E. George: Where it is desired to produce out-of-step conditions without too much shock to the system, this can be accomplished by lowering the excitation on the plant while building up on the kw. output. By juggling the excitation and governor opening it is fairly easy to control surging between the plant and the rest of the system. The effect of various out-of-step conditions on relays is very interesting.

One point particularly worthy of comment in this paper is the possibility of getting machines back in step without taking them off of the bus. This saves the time required to resynchronize the machine which may be excessive if there is trouble on the system.

For several years we have instructed our operators, in case of out-of-step conditions, to juggle the field rheostat and governor controls and try to get the equipment back in step without disconnecting and paralleling. In most cases it has been possible to accomplish this successfully.

Phillip Sporn: This paper forcefully brings out the fact that although governors have been in use in connection with the operation of steam turbines for many, many years, the real action of such governors, particularly their action under times other than normal, has not been well understood and certainly not understood clearly enough to be able to deduct therefrom the amount ultimately contributed by the governor itself toward the total disturbance. The tests which were carried out as described in this paper show that the governor's contribution to the total disturbance under certain conditions of system fault is no negligible portion.

As is also brought out in the paper, this out-of-step condition between generators in the same station or between generators and the system, is no uncommon occurrence. It undoubtedly happens many times but before anything really serious develops, the hunting dies down, the generators pull back into synchronism and the entire disturbance is summarized and frequently forgotten under the general heading of "surge on the system." Fig. 1 shows a high-speed chart taken at the Turner substation of the Appalachian Electric Power Company during a condition of a severe short on a low-voltage bank, approximately 50 miles away. It will be noted that this condition is very analogous to the condition of instability shown in Fig. 7B of the paper under Test 34. In this case the taking off by hand of a turbine unit at Cabin Creek, a generating station located approximately 25 miles from Turner, resulted in the system pulling into synchronism.

*Operating Characteristics of Turbine Governors, by T. E. Purcell and A. P. Hayward, A. I. E. E. Trans., April 1930, p. 715.

Fig. 2 shows another chart taken at the Turner substation during lightning disturbance on the Turner-Cabin Creek line. It will be seen in this case that the instability which developed at Cabin Creek on unit No. 6, due to a fault condition on the Turner-Cabin Creek line, was sufficient to pull the unit out of synchronism, with the result that it tripped off the line from overspeed. The situation is very similar to case B in Fig. 7.

Fig. 3 shows a record taken on a Hall recorder at the Glen Lyn generating station. The upper record shows ground current and the lower three records show line-to-line voltages on the 132-kv. bus. During a lightning storm a double circuit fault occurred between Glen Lyn generating station and the Switchback substation to the west. Both circuits tripped and the station was practically unloaded resulting in violent swinging for about three seconds and subsequent less severe swinging for another three seconds until the generators finally pulled in step and the voltage became normal.

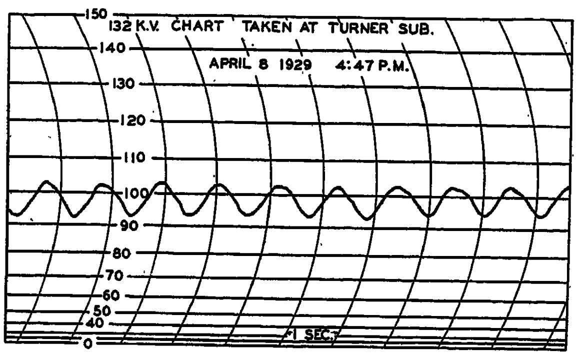

Fig. 1

It is obvious that in all these conditions, while the governor may not have been a direct contributing cause for the violence of the fluctuations, it certainly did not contribute anything definite early enough in the disturbance to materially reduce or minimize the disturbance. On the other hand, the governor offers a definite point in the system at which to apply restraining forces under disturbance conditions. The authors show in this paper a development which offers a definite remedial force toward the mitigation of some of these disturbances. There is no question but that the intelligent application of the watt principle in governing as brought about by the authors will be of material assistance in the operation of large power systems under disturbance conditions.

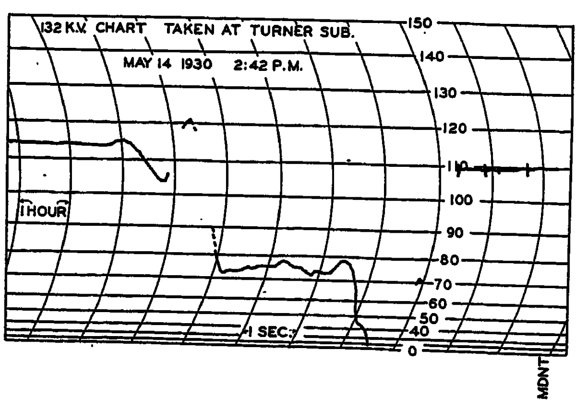

Fig. 2

It may be interesting in connection with this to tell of some of the other remedial measures that have been taken at the Stanton Plant to overcome some of the difficulties that have been experienced with instability between two generators. The first step after the experience with instability was to reduce the load on the generating station under disturbance condition to about 60,000 kw., which is only 66 per cent of the normal system rating. This is a very uneconomical way of bringing about stability and could not be maintained for any extensive period. The problem was carefully analyzed from every angle and as a result the following measures were decided upon:

1. As a first step, high-speed relays in the form of plunger type ground relays were installed on all outgoing circuits and set so that they would operate on ground faults for about 80 per cent of the distance from the generating station to the nearest substation.

2. This station has two 66,000-volt buses, one a main and the other a reserve, each with its own circuit breakers. One set of these breakers, *i. e.*, the breakers on one entire bus, is being cut over for high-speed operation. It is estimated that this combination of high-speed relays and circuit breakers will clear ground faults in a maximum of 10 cycles, for faults occurring on any outgoing line for about 80 per cent of the distance between the generating station and nearest substations.

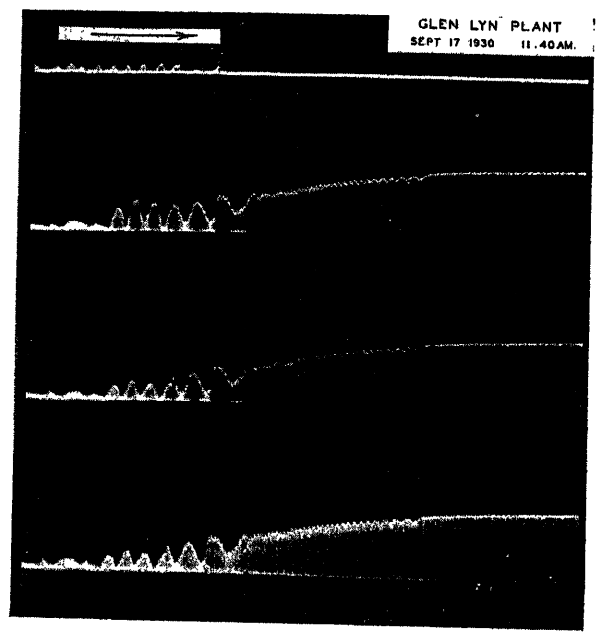

Fig. 3

3. The installation of watt governor mechanisms along the lines pointed out in the papers is being studied at the present time with a probability that the installation will be proceeded with as soon as some of the pertinent details are worked out.

Subsequent to the installation of the high-speed relays but before the breakers were cut over to high speed, a very severe lightning storm occurred during which two faults occurred near the Stanton station, one on the Scranton system, and the other a little later, on the Pennsylvania Power and Light Company system. During this period the generators were carrying 80,000 kw. and no trouble of any kind was experienced at the plant. The generators rode through the storm in excellent shape although before these changes were made they had invariably developed instability and tripped off the line.

R. C. Buell: Mr. Purcell expresses surprise "that the tur-

bines under test overspeeded enough to trip the emergency governors when loads in excess of 60 per cent of rated capacity were dropped." It should be remembered that the turbines at Stanton are of the reheat type with the speed governor controlling only the high-pressure steam entering the turbine, no control is provided for the steam as it comes from the reheat boiler. At full load there is sufficient stored energy in this boiler to cause a speed rise in excess of 10 per cent, if full load is dropped. The intercepting valve located in the return line from this boiler and operated only from the emergency overspeed governor prevents excessive rise above 10 per cent.

Calculation showed that even with the reheat boiler out of service and the by-pass valve open and reheat valves shut, the entrained steam in the lines to the boiler contained sufficient steam to overspeed the turbine.

In the ordinary turbine without reheat the speed governor is fast enough to easily prevent tripping the emergency overspeed governor at 10 per cent above normal when full load is dropped.

We believe Mr. Purcell has interpreted our remarks in regard to the complexity of the problem of holding the generators in synchronism with the rest of the system as applying also to the load dropping test. The two problems are entirely different, for in one case the turbine speed must not increase more than 1 or 2 per cent, while in the other a 10 per cent rise is permissible.

The Ohio Falls Hydroelectric Station at Louisville, Kentucky

BY R. M. STANLEY[1]
Fellow, A. I. E. E.

and

E. D. WOOD[2]
Member, A. I. E. E.

Synopsis.—*This paper is a description of the Ohio Falls Hydroelectric Station at Louisville, Ky. The development is a low-head, run-of-river plant and a combined navigation and power dam. The dam is a part of the U. S. Government Ohio River canalization project.*

Eight units, with a total installed capacity of 105,000 hp. operate on a maximum head of 37 ft. and deliver power to the systems of the Louisville Gas and Electric Company.

Several novel electrical features are embodied in the design of this plant. Both automatic and supervisory control equipment is employed and is housed in closed steel cabinets.

A miniature switchboard with complete control and supervision of each unit on a panel four in. wide is another new idea that is used in station control.

* * * * *

Introduction

When in 1923 the U. S. Government, in carrying out its plans for the complete canalization of the Ohio River, decided to construct a dam at Louisville of a height sufficient to give a maximum drop of 37 ft. between the upper and lower pools, the economic and engineering aspects made feasible the construction of a hydroelectric generating station.

Actual construction was begun in 1925 and the plant was turned over to the operating company in the early part of 1928.

Site

The Ohio River at Louisville descends about 28 ft. in a distance of two miles over a series of rapids. This is the only fall of any size in the entire length of the river, the general slope of which is very flat.

This natural fall has always been looked upon as a potential power source and was actually used on a relatively small scale by a flour mill built by the Tarascan Brothers early in the nineteenth century. It is interesting to note that these early pioneers in water power development chose a site only a few hundred feet away from that now used by the hydroelectric development.

Test borings made in the exposed limestone at the foot of the rapids indicated that foundation conditions there were sufficiently good to support the contemplated structure.

A power house site was chosen on the Kentucky side of the river within the limits of the city of Louisville. This latter fact was important because it insured a ready market for the power to be generated; more important still, steam generating capacity in sufficient amount to back up the intermittent power available from the run-of-river development was already installed within a few miles of the site.

In granting a license to the Louisville Gas and Electric Company, the Federal Power Commission instructed that company and the District Office of the U. S. Engineer Corporation to work together on the plans for the development. The engineers for the company prepared the plans for the power plant, the U. S. Engineers worked out the design of the dam, and the entire project was built by the construction forces of the Byllesby Engineering and Management Corporation.

Water Supply

The area drained by the Ohio River above Louisville is extensive, amounting to over 91,000 sq. mi. and extending well into New York, Pennsylvania, Virginia, and Maryland.

Despite this large area and the generous rainfall on the western slopes of the Appalachians, the natural flow of the river is unstable, varying from about 792,000 sec.-ft. at the time of maximum flood to 5,000 sec.-ft. or less during summer droughts. Due to a restricted river channel for a number of miles below the city, this variable flow causes a maximum variation in the river stage at Louisville of 65 ft. This results in a variable head at the power house that ranges from 37 ft. at times of low flow to zero at high flow.

The Dam

The dam is a concrete structure with steel gates and guides and timber wickets resting upon a rock foundation into which was cut a 4 by 3 ft. keyway. It extends upstream from the north end of the power house, paralleling the river banks approximately 7,000 ft., thence northward to the Indiana Shore. It is the longest and highest dam on the Ohio River, the entire length being 8,680 ft., including two 91-ft. beartraps, 3,600-ft. boule weir and 860-ft. chanoine pass.

The movable sections, operated by derrick boats by the U. S. Engineer Department, have a discharge capacity of 350,000 sec.-ft.

The beartraps are operated by hydraulic pressure and have a discharge capacity of 32,000 sec.-ft. During normal flow conditions, pool regulation is accomplished through maneuvering of boule and pass, leaving

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the beartraps to be operated during emergency cases and high water.

Fig. 1 shows a map of the river adjacent to Louisville with the dam and hydro station. Fig. 2 is an airplane view taken from below the hydro station also showing the dam and a portion of the city of Louisville in the background.

Power Station

The water-level variation had much to do with the design of the station. The entrance is located four feet above maximum high water. To save in superstructure, the generator-room floor is depressed 16 ft. below the entrance level. The water wheels are placed near low-water level.

Each unit passes a flow of about 4,000 cu. ft. per sec. so that the total water capacity of the plant is 32,000 cu. ft. per sec. In order to pass this large flow under a comparatively low head and maintain the plant efficiency, the water passages were made large, the racks for each unit being 40 ft. deep and the units being spaced on 58 ft. centers. Between units 2 and 3 and between 5 and 6 the spacing is increased to 64 ft. where expansion joints are carried through the structure.

Eight units, each having a capacity of 13,500 hp. at 37 ft. head are installed and provision is made for two additional units at the northern end of the station.

The generator room is 44 ft. wide and 508 ft. long. There are two floor levels below the generator floor. The lowest floor contains the tanks for governor oil and pumps supplying cooling water to the closed generator ventilating system. The intermediate floor holds the governor pressure tanks, oil pressure pumps, and pumps supplying cooling water for the transformers. At the southern or shore end of the station is located a sump with automatic pumps which takes care of all leakage from the stuffing boxes on the turbine shafts and at the expansion joints.

A standard gage railroad track leads into the shore end of the building where there is an unloading platform served by the house crane.

Fig. 3 is a view of the station taken from the upstream side showing a 25-ton gantry crane for serving the headworks. Headworks for two additional units are shown on the right.

Fig. 4 shows the interior of the generator room.

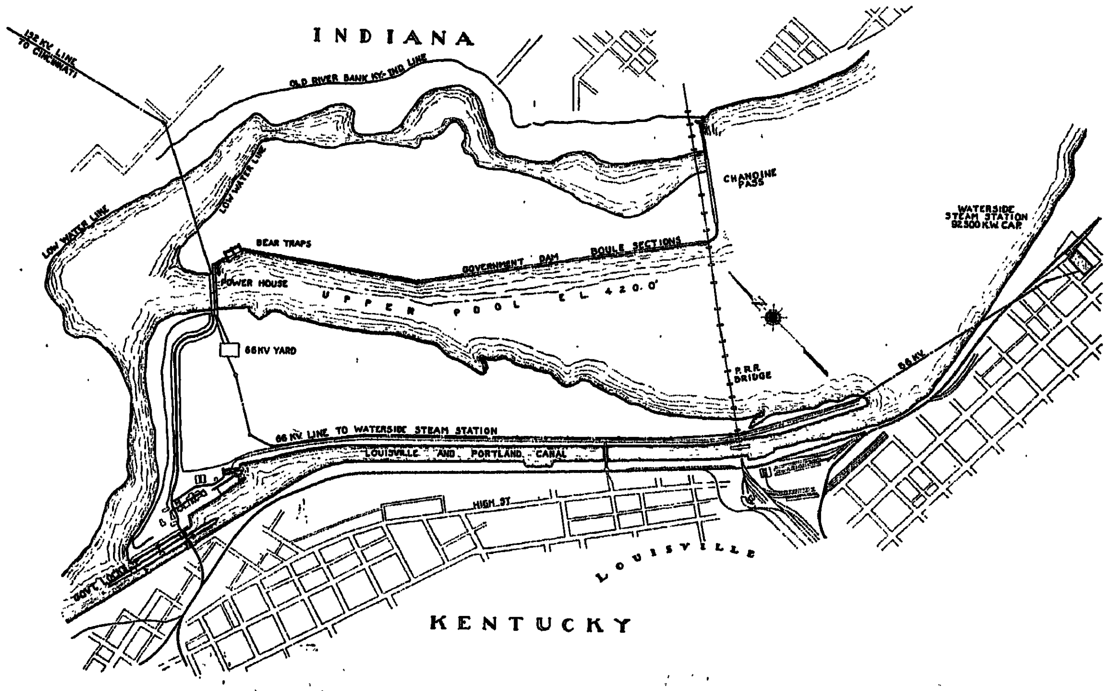

Fig. 1—Map of Dam and Hydroelectric Station Site

Water Wheels

With a maximum flow of 4,000 sec.-ft. through each unit, three intake openings with a total cross-sectional area of 1,400 sq. ft. are necessary in the concrete scroll case of each unit. These openings are equipped with

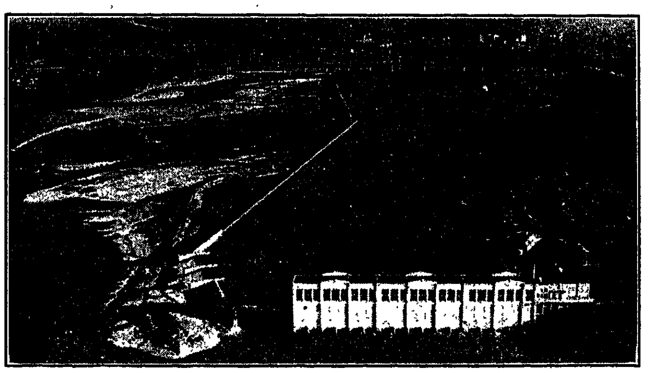

Fig. 2—Airplane View of Dam and Hydroelectric Station

Headworks for future two units are seen at the left of the station. Pennsylvania R. R. Bridge and sky-line of Louisville in background

trash racks and necessary guides for roller gates and stop logs to be used in case of emergency.

The hydraucone is used, which, due to decreasing the velocity of discharge, keeps the loss in energy in the tailwater down to a minimum.

A five-blade propeller type axial flow runner, designed to produce 13,500 hp. at 37 ft. net effective head at a speed of 100 rev. per min. was selected because of its ability to operate under a range of heads varying from the maximum of 37 ft. down to 8 ft.

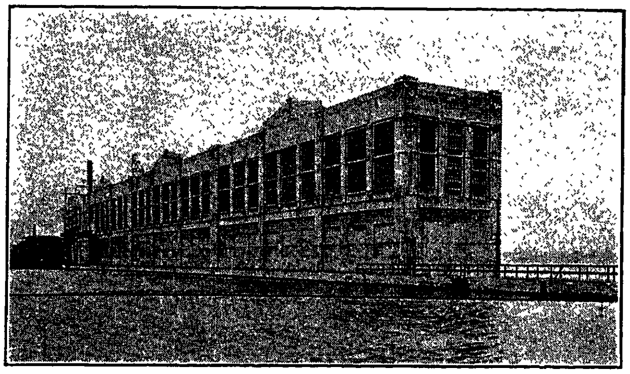

Fig. 3—Hydroelectric Station from Upstream Side

Headworks for future two units are seen on the right. Gantry crane for serving headworks can be seen

The runner of cast steel is 15 ft. in diameter and weighs 20 tons. It is coupled to the rotor by 61 ft. of 23 in. diameter shaft. The combined weight of 125 tons is suspended from a spring type thrust bearing. Four guide bearings, three of which are babbit and one lignum vitae are used because of the long shaft.

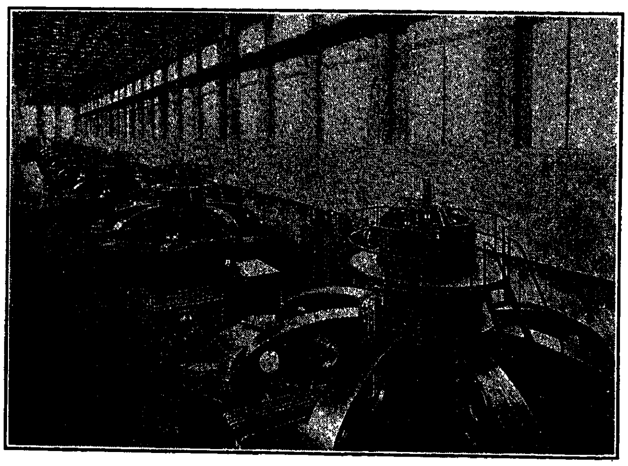

Fig. 4—Generator Room

8-12,550-kv-a. water-wheel-driven generators with surface air coolers. Oil circuit breakers, switchboard, and governor for one unit can be seen

Electrically-driven fly-ball governors, automatically operated, provide positive control to servo motors and guide vane latch. The servo motors and latch are mounted directly on the cover plate, thus eliminating strains on the shift ring.

General Electrical Layout

The extreme length of the power house was determined solely by hydraulic requirements and made necessary an unusual arrangement of the generator electrical equipment to fit it into the available space.

The unit type of construction is used as regards the generator oil circuit breakers, auxiliaries, and switchboard panels.

The main buses are supported on a steel structure along the upstream wall of the station just below the windows and are totally enclosed in a sheet steel housing.

Generator oil circuit breakers are located on the main floor just below the main buses and as close to the machines as possible. Connections between the generators and oil circuit breakers are of flat copper bar housed in sheet steel flues.

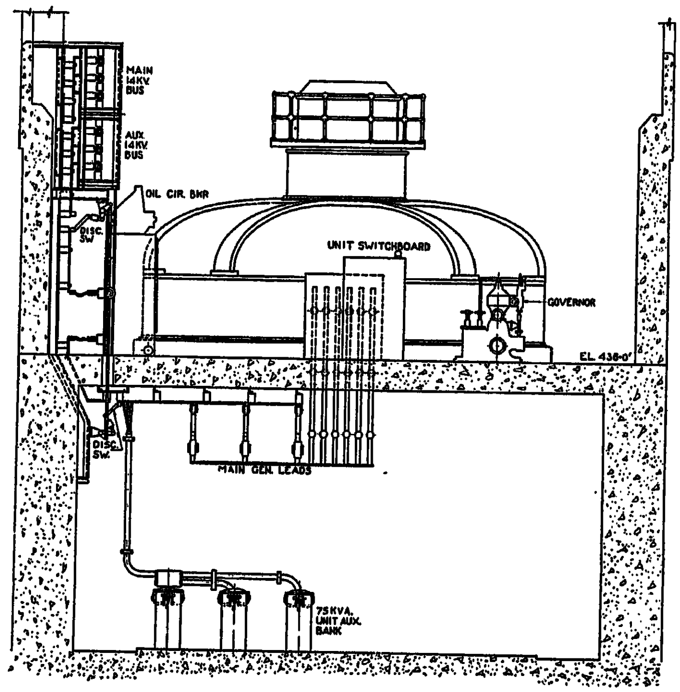

Fig. 5—Cross-Section of Station Showing Generator Lead Connections

Main and auxiliary buses are shown on upper left with generator gang operated disconnect switches and oil circuit breaker below. Switchboard enclosure is in center and generator governor to the right. The unit 75-kv-a. auxiliary transformer bank is on floor below with connections made solidly to the generator leads

The generator switchboard panels are also located on the main floor near the generator and governor.

This grouping of the generator electrical equipment in close proximity to the individual units results in exceptionally short bus connections between the generators and oil circuit breakers and short control conduit and cable runs between the generators, switchboards, governors, and oil circuit breakers.

Fig. 5 is a section through the generator room showing a generator with associated oil circuit breaker, disconnect switches, switchboard housing, and governor.

The main and auxiliary buses are also shown with connections to the generator.

Fig. 6 is a view on the generator floor showing one unit with its associated oil circuit breakers for connection to the main and auxiliary buses, the unit switchboard and housing, and the governor.

Generators

Generators are of revolving field type, rated at 12,550 kv-a., 14,000 volts at 100 rev. per min. and equipped with direct-connected exciters mounted on the thrust bearing housing with field current collector rings mounted above the exciter.

Fig. 6—Automatic Switching Equipment

Truck mounted oil circuit breakers for connecting unit to main or auxiliary bus are seen with the unit switchboard and governor

The generator stator frame which is of welded steel construction, supports the weight of the rotor, thrust bearing, upper guide bearing, and the remaining rotating parts which include the entire length of shaft, water-wheel runner and water thrust.

Armature Winding

From the armature winding 12 leads are brought out to a terminal board to permit differential protection and also for the purpose of changing the operating characteristics. For full load operation the windings are normally connected two-circuit Y but for light loads they may be connected one-circuit delta.

This change of connections is readily accomplished by means of gang operated disconnect switches. The improved efficiency of the delta connection as compared with the Y connection is computed as being 2.1 per cent at 10 per cent full load to 0.5 per cent at 75 per cent full load, 0.8 power factor. Above 75 per cent full load the Y connection is again used and normal efficiencies are obtained.

Ventilation

Generator ventilation in this station is similar to that used for many years on steam turbo-generators, heated air from the generator armature and field coils being forced by fans on the rotating member through water coolers located at four points on the periphery of the armature frame and at floor level. The air thus cooled is driven down through suitable openings in the concrete foundation to a space below the machine, formed by the circular foundation and a horizontal steel diaphram. This cooled air is then drawn by the generator fans up through the machine to be forced out again and through the coolers.

This is the first application of coolers to hydro-generators and has proved exceptionally successful and valuable in this instance because of the high air temperatures existing through a large part of the year and the smoke and dust in the outside atmosphere. The latter is due to railroads and factories surrounding the development.

Leakage of air is made up by the installation in the suction side of the system of Reed air filters which remove dust and dirt from entering make-up air.

The generator armature and field coils are found to be practically as clean as when installed and thus the efficiency of the units is kept at the original value and the life of the installation is preserved.

Fig. 7 shows a section through the generator and the cooling equipment with the direction of air flow indicated by means of arrows

Oil Circuit Breakers

The generator oil circuit breakers are truck type, motor operated, having an interrupting capacity of 500,000 kv-a. standard duty cycle. One set of disconnect switches on the bus and one on the machine side of each oil circuit breaker are operated from a single hand operating mechanism located at the breaker.

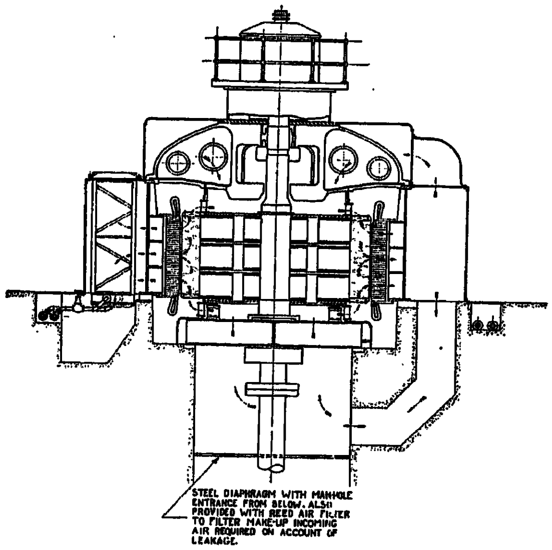

Fig. 7—Cross-Section of Generator and Air Cooling System

Arrows indicate the direction of air flow through armature and field coils. Filters for supplying make-up air are not shown

Necessary current and potential transformers for metering and control are connected in the short bus runs between the machine and breakers.

Switchboards

Manual and automatic control of the generators, outgoing lines and station service banks is performed

by means of standard panels and control equipment located in close proximity to the equipment controlled. The switchboards with the associated relays, contactors and control switches are mounted in sheet steel housings for protection of the equipment.

Control and meter circuits are brought to the switchboards by means of Greenfield cable through multi-circuit train couplers so that the board can be entirely isolated and removed.

Fig. 8 shows the front of a generator switchboard

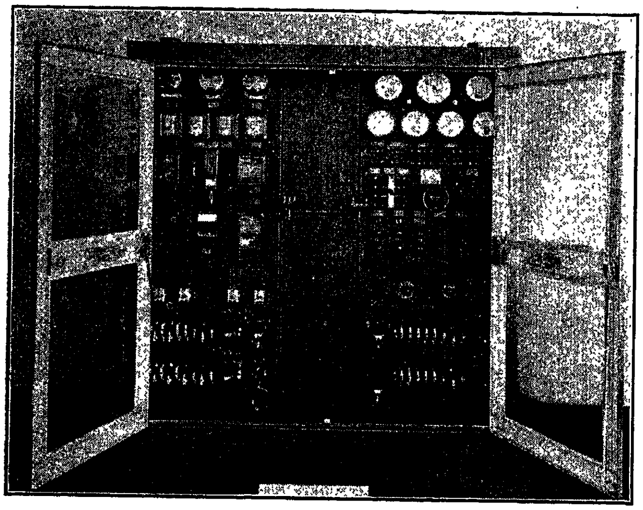

FIG. 8—GENERATOR SWITCHBOARD

Instruments for manual and automatic control of generator unit shown on panels enclosed in steel housing. Two pilot lights on top of housing indicate to floor attendant that unit is to be started. Rear connections to pull-button switch which is operated to start unit are seen on right-hand door. These doors are closed and locked normally

and housing, and Fig. 9 illustrates a rear view of the same board. The multi-circuit train couplers are located at the bottom of the board.

AUXILIARIES—MECHANICAL

Each unit, designed as a station complete within itself, has its individual auxiliaries automatically and independently operated. Included in these are bearing and governor oil systems, oil filtration, air operated brakes, cooling water supply to generator coolers and thrust bearings and water supply to lignum vitae bearings.

Realizing that auxiliary failures mean jeopardized service, certain additional features were included in order to insure more dependable operation. A complete station bearing oil system, automatically operated, supplies each generator with the one and one-half gallons per minute required for its operation. This oil can be distributed to the unit bearings and the overflow in the unit system returns to the station filter.

The governor oil pressure systems are equipped with pressure control relay gages, limiting normal operating pressure between 150 and 175 lb., designed to shut down a unit in the event the oil pressure drops to 130 lb. The tanks are connected to headers in groups of three, both on the pressure and storage side, in order to insure continuous operation in case of failure of any individual unit system.

A bank of three 4-in. centrifugal cooling water pumps supplies the house header and transformer banks. The house header which is connected to the city water supply, is also connected to all generator cooling units.

All waste water, leakage and seepage, drains to one common sump, from which automatic pumps discharge the water into the tailrace, pumping it over the high water level.

AUXILIARIES—ELECTRICAL

The scheme of unit auxiliary equipment is also carried out as regards electrical equipment in that all of of the auxiliaries, with the exception of compressed air for the brakes and d-c. control voltage, are fed directly from each generating unit. The auxiliaries associated with the operation of the individual units are: one 30-hp. governor oil-pressure pump, one 7.5-hp. generator cooling-water pump and one ¾-hp. governor fly-ball motor. These auxiliaries are fed from the main generator by a step down transformer bank consisting of three 25-kv-a. single-phase 13,800- to 230-volt transformers. The 13,800-volt side of this transformer bank is connected directly to the generator leads, no fuses, oil circuit breakers or disconnect

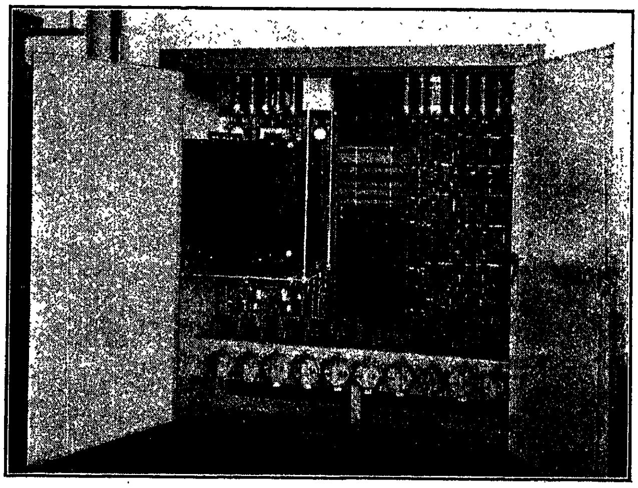

FIG. 9—REAR OF GENERATOR SWITCHBOARD

Multi-circuit train couplers through which meter and control circuits pass are at the bottom

switches being used. In starting a unit the governor fly ball and oil pressure pump motors are fed from a 230-volt station auxiliary bus. As the generator comes up to speed and 85 per cent of normal voltage is reached the governor fly-ball motor is automatically transferred to the unit feed. The governor oil-pressure motor is transferred from the station feed to the unit feed manually. The generator cooling-water pump motor is fed direct from the unit transformer bank at all times. The generator exciters are direct-connected to the main shaft.

The station auxiliary units used for house and emergency service for the generating units are as follows:

Two, 35-hp. battery charging motor-generator sets, two 15-hp. sump pumps, emergency 100 hp. sump and lignum vitae bearing water supply, three 25-hp. transformer and emergency thrust-bearing cooling-water pumps, two 15-hp. ventilating system motors, one 10-hp. air-compressor motor automatically controlled for use on brakes and governors, one 15-hp. air compressor motor for station purposes, one 3-hp. vacuum pump motor, two ¾-hp. and one 1-hp. oiling system motor, power house crane of 225 total hp. head works Gantry crane of 57.5 total hp.

The motors that are in duplicate are fed from two separate 230-volt buses. These two buses are supplied by a 600-kv-a. 13,800- to 230-volt transformer bank which can be energized from any one of three separate sources, namely the main or the auxiliary 14-kv. station buses, or an incoming 13-kv. feeder from the steam station. The selection of the feed to this 600-kv-a. bank is entirely automatic in that should a failure occur on the normal source, the source of next preference is automatically selected and connected to the transformer bank. In case it is necessary to take the 600-kv-a. bank out of service the station auxiliary motors essential to the operation of the plant can be fed from one of the 75-kv-a. transformer banks associated with each generator.

The station lights are normally fed from one 13,800- to 230-115-volt transformer energized from the same source as the 600-kv-a. power bank. In case of extreme emergency the most important lights are automatically transferred over to the station battery.

Fig. 5 shows the location of the unit 75-kv-a. transformer bank and connections to the generator leads.

Transformer Banks

Two transformer banks of 62,500 kv-a. and 56,250 kv-a. respectively, are located on a platform outside the building. The 62,500-kv-a. bank is two-winding, stepping from 14,000 to 66,000 volts and supplying a 75,000-kv-a. transmission line to Waterside Station.

The 56,250-kv-a. bank is three-winding, stepping from 14,000 to 66,000 and 132,000 volts. A 132-kv., 82-mile transmission line supplies power to Columbia Steam Station southwest of Cincinnati. The 66-kv. winding connects to the present line to Waterside.

The 132-kv. winding is supplied with a tap changing under load equipment which permits a 10 per cent variation of voltage in four 2½ per cent steps, up and down, to suit load conditions.

The low-tension connections of these banks are made to the main and auxiliary station buses through 3,000-ampere gang-operated disconnect switches on the bus and transformer sides of cell-mounted, motor-operated oil circuit breakers with an interrupting capacity of 800,000 kv-a. standard duty cycle. This breaker equipment together with the low-tension delta bus structures and instrument transformers is located in an extension of the power station along side the transformer platform.

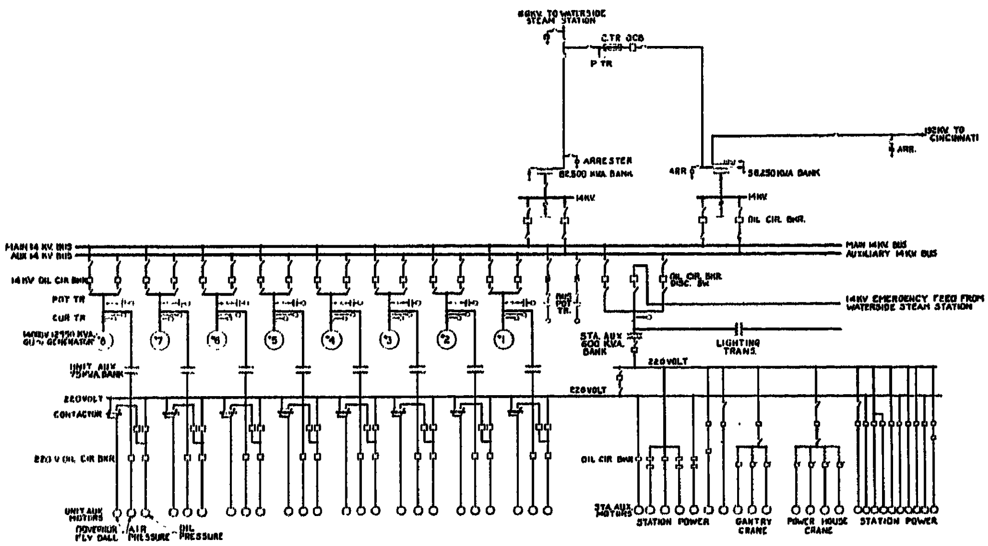

Fig. 10—One-Line Diagram of Station

14,000-, 66,000- and 132,000-volt buses are shown and also 230-volt unit and station auxiliary buses

The 132-kv buses extend over the roof of the station where connections are made to the Cincinnati line.

The 66-kv. connections from the two banks are carried overhead to the switch yard adjacent to the station where the tie for the Waterside line is completed.

A one-line diagram of the high and low tension connections is shown in Fig. 10.

Fig. 11 shows the 14,000-volt connections to the 56,250-kv-a. transformer bank.

14,000-Volt Buses and Connections

Main and auxiliary 14,000-volt buses extend the entire length of the station with the generator switching equipment located near the individual generators. This arrangement eliminates the long generator con-

nections that would be necessary if the typical scheme of a switch gallery at some remote point in the station, had been used. It also results in a corresponding reduction in the length of control and instrument conduit runs and brings all of the main equipment associated

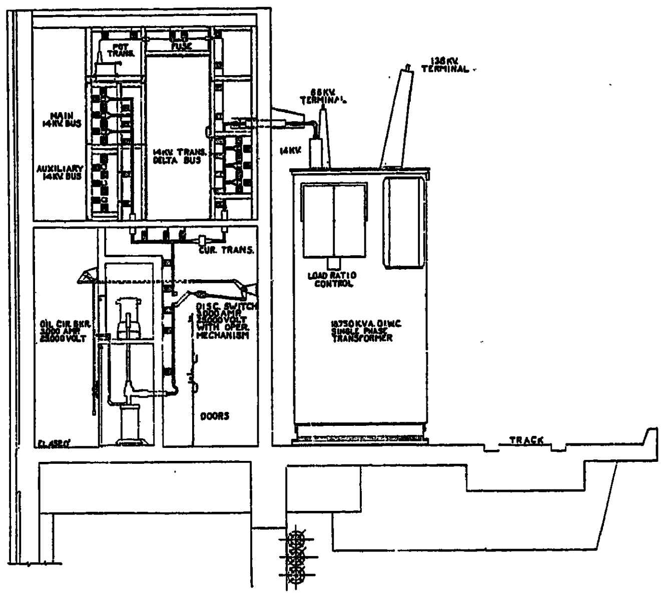

FIG. 11—14,000-VOLT TRANSFORMER CONNECTIONS

with the control within a very short distance of the unit.

The two buses are arranged vertically on the outside wall of the station with three-way bus supports mounted on an electrically welded steel structure, and the whole enclosed by steel plates. Each phase is of the box-bus type of construction with over-all dimensions of 4 by 4½ in. of ½ in. copper bar. Taps from the buses are of flat bar construction. The total length of the two buses is approximately 620 ft. with no portion of the bus or connections taped.

SUPERVISORY CONTROL

A miniature switchboard is used to provide centralized control of the operations of the station. This supervisory board is centrally located on the generator floor between units 4 and 5. The control equipment consists of a two-position control key for each circuit breaker or other device controlled, with three indicating lamps for each key. The red and green lamps indicate the closed or open position of the breaker respectively, and the white lamp indicates that the position of the controlled device does not correspond with the position of the control key.

In addition to the supervisory control keys, the miniature switchboard contains voltmeters, reactive volt-ampere meters, wattmeters, switches for raising and lowering load and switches for regulating voltage. Insulating potential transformers, 110/110 volts, are used in the secondary circuits of the generator and transformer bank instrument potential transformers for meters on the supervisory panels and with 10/1-0.5 ampere transformers in the secondary circuits of the current transformers.

Control and meter circuits are taken from the supervisory panels by means of low-voltage telephone wires to a terminal box below the generator room floor. From this terminal box to an auxiliary terminal box associated with the unit switchboards, lead-covered, 16-pair telephone cable in rigid conduit is used, there being one such cable between the supervisory panels and each generator, transformer bank, and station auxiliary switchboard.

Fig. 12 shows the general arrangement of circuits between the supervisory panels and the various unit switchboards.

Fig. 13 also shows the same scheme as applied to an individual generating unit, the two transformer banks, and the station auxiliary transformer bank.

A front view of the supervisory board is shown in Fig. 14, and Fig. 15 shows the associated relay panel mounted in the rear.

GENERATOR CONTROL

The operation of the control equipment is briefly described as follows:

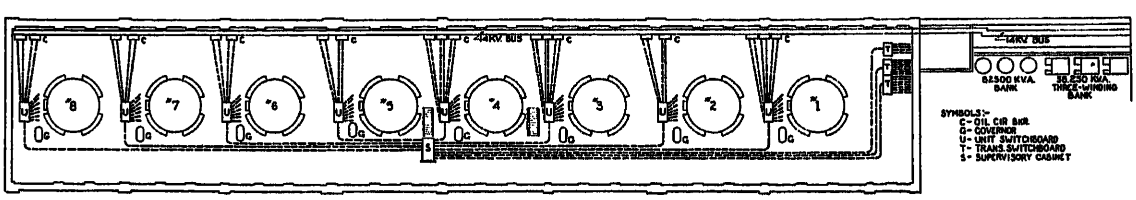

FIG. 12—CONTROL SCHEMATIC

Circuits between supervisory panels and generator, station auxiliary, and transformer switchboards are shown, also control circuits from these switchboards to the equipment controlled

The operator at the supervisory panel selects the bus to which the machine is to be synchronized by turning the bus selector key. To give the starting indication he turns the "Start and Stop" control key to the "Start" position which notifies the floor attendant to stand by for starting the unit. He also selects the type of synchronizing to be used, whether automatic or self synchronizing. The floor attendant then checks to see that the gate limit stop is set for full-speed no-load value of head and closes a pull-button control switch on the generator cubicle door to give the actual starting indication to the unit. If all protective devices are in

their normal or reset positions, the governor solenoid picks up and opens the pilot valve which allows oil pressure to act on the gates to open them. At the same time the water-wheel brakes are released and the machine starts. The fly-ball motor of the governor is connected to the 60-cycle station auxiliary bus which prevents the machine from overspeeding and the governor synchronizing motor runs to the maximum speed position to allow rapid acceleration of the water wheel.

If automatic synchronizing has been selected, the field contactor is closed to apply field to the generator when the exciter voltage has built up to about 80 per cent and the fly-ball motor is now connected through potential transformers to the terminals of the generator. The water-wheel gates are closed, the generator is disconnected from the bus at the "running light" position, the field is deenergized, and the brakes are applied after the water-wheel has reached as low a speed as it will obtain without the application of the brakes.

Protective Devices

The automatic equipment will shut down the unit in case of a-c. overvoltage, grounded windings, overheated bearings, loss of field, overspeed, or low oil pressure. If the shut down is caused by overvoltage or grounded windings, the generator is immediately disconnected from the bus and the field is killed. If the shutdown is due to any other cause the load is first reduced before the generator is disconnected.

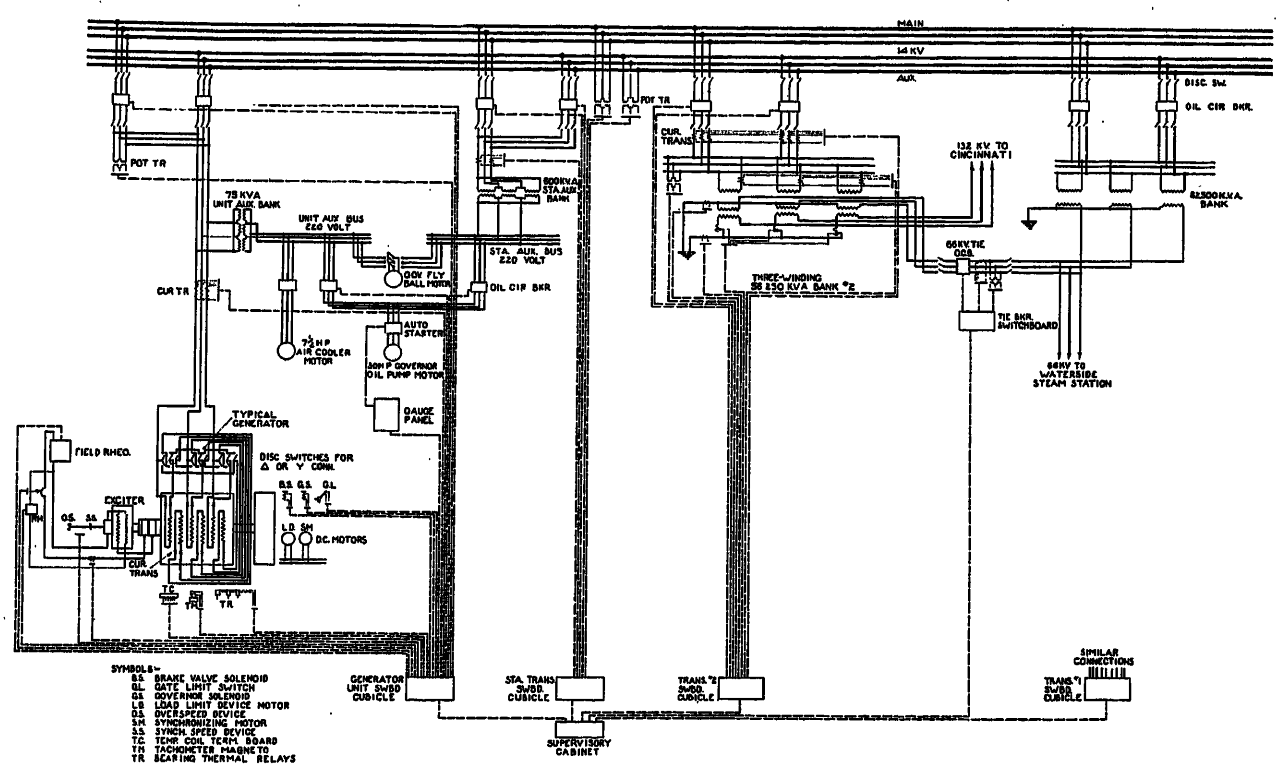

Fig. 13—Three-Line Schematic of Generator

Station auxiliary and transformer connections and control

When the machine reaches 98 per cent synchronous speed, the speed regulating relay automatically adjusts the speed until the generator is synchronized with the bus at which time the synchronizing relays operate to close the oil circuit breaker to connect the generator to the bus. The load is then adjusted by the operator at the supervisory panel.

If self synchronizing has been selected, the machine comes up to 98 per cent synchronous speed without field current and is closed to the bus selected as an induction motor. Seven cycles later the unit is pulled into step by the application of generator field current.

Shut Down

The unit may be shut down at any time by turning the "Start and Stop" key to the "Stop" position.

Transformer Equipment Control

The operator gives the closing indication at the supervisory panel to either breaker of either transformer bank by turning the control key to the "Close" position. The equipment is designed for either stub or multiple feed. The selective control relay and the synchronizing devices determine the type of feed and give the closing indication to the circuit breaker when conditions are correct. This circuit breaker is tripped in case of reverse over current.

The circuit breakers may be controlled manually by placing the transfer switch in the "Manual" position.

Station Service Equipment Control

The station service bus is normally connected through a power transformer bank to the main bus.

If the voltage on this bus fails, the breaker is opened and the station service equipment is connected to the auxiliary bus, if energized, or to the emergency bus if this bus is energized and the auxiliary bus is not. When normal voltage returns to the main bus, the station service equipment is disconnected from the auxiliary or emergency bus and is connected to the main bus.

Safety Devices

The generator and station service oil circuit breakers are equipped with mechanical interlocks which pre-

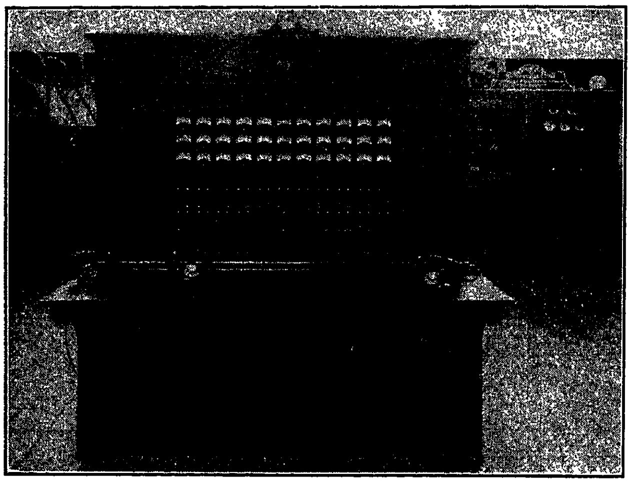

Fig. 14—Supervisory Miniature Switchboard

Each four in. panel contains complete meter and control equipment for supervising the operation of a generator, station auxiliary bank or outgoing line. Space is provided for future additions

vent the truck from being removed or replaced when the oil circuit breaker is in a closed position. Interlocks are also provided to prevent the removal or replacement of the circuit breaker cell doors when the circuit breaker is closed or the truck is in the operating position.

Other safety features incorporated in the automatic control of the generators include the following:

A generator cannot be synchronized with the bus or the breaker closed unless the truck is completely in its housing.

A machine will be shut down and locked out in case of overspeed, excessive a-c. voltage, low governor oil pressure, overheated bearing, excitation failure and short circuit or ground in the armature windings.

The generator cannot be reconnected to the bus without going through the normal sequence of starting in case the generator breaker is opened for any reason.

Heating and Ventilating

Both heating and ventilating are taken care of in combined units. The major layout consists of two complete systems, one at each end of the station designed to take air from the outside or from the generator room for recirculating. In either case air is drawn into the fan room through air filters and heating units. It is then forced through ducts to the lower floor from which point it rises to the generator room through stairways and the other openings and escapes through windows and louvers on the roof. None of this air passes through the generators as is customary in plants of normal design.

Two types of heating medium are used. In extremely cold weather and at times when the plant is shut down due to high water, steam is furnished by a 125-hp. boiler located in an annex of the power station. At other times, electrical heating coils supplied with off-peak power are used.

The generator field rheostats are located on the floor directly below the generators and advantage is taken of their heat losses, this heat being discharged directly into the generator room through openings provided in the floor. This also affords good ventilation to the rheostats in summer.

Operation

The operation of this station depends entirely on the flow of the river. Low water and small volume or the rapid and excessive rise of tailwater under flood conditions results in a curtailment of power output. The average yearly complete shutdown due to high water is 45 days. As far as possible, a constant pool of 420 ft. above sea level must be maintained for navigation

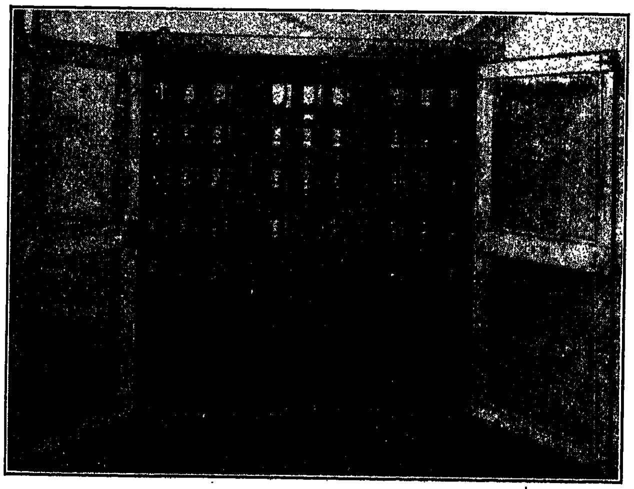

Fig. 15—Rear of Supervisory Miniature Switchboard

purposes. This necessitates operation at highest point of efficiency during low water periods, at which time the plant operation is the governing factor of the pool stage. In case of emergency, for short periods, all available equipment can be put into service within two minutes. During periods when the flow exceeds the discharge capacity of the station, efficiencies are disregarded and pool stages are controlled by manipulation of dams and plant operation combined.

Economics of Operation

There has been a considerable saving in both time

and labor costs in operating the Ohio Falls Hydro Station; this saving resulting from the use of automatic control equipment.

Only one switchboard operator is required on a shift. To bring a unit in on the line he turns a control key, thereafter the automatic equipment functions to start auxiliary motors, release brakes, open water gates, apply excitation and synchronize the unit on the bus. It is estimated that these automatic features have effected a yearly savings, equivalent to two operators' salaries. There has also been a saving in the number of hydraulic operators needed at this station. Several factors account for this saving, simplicity and flexibility of operation, general arrangement of equipment, and the complete use of automatic protective equipment which in particular has proven to be dependable. Where we use three hydraulic men per shift for the actual operation of these eight generators, five men per shift would have been required without the above features.

The maintenance costs on this station have been somewhat lower than were at first expected. It is believed that the use of automatic equipment has resulted in less maintenance rather than more. Once the equipment is properly adjusted, routine tests and inspection have been the smallest maintenance item. These tests are conducted weekly and require only the part time of one maintenance electrician.

The miniature switchboard will permit further economies and may be located in a future adjacent steam station in which case one operator can control both stations.

Discussion

Chester Lichtenberg: The electrical features constituting the control of the Ohio Falls Hydroelectric Station represent a distinct advance in the art. They utilize well established principles. They combine these in a unique fashion, and permit not only a lower than usual installation cost, but also permit extensions to be made from time to time in the most economical fashion.

The design is unique in that each generating unit is complete in itself. The water-wheel, generator, exciter, governor, electrical control, and oil circuit breakers, are individual for each unit. There are only 4 points in common. They are as follows: (1) forebay, (2) high-voltage buses, (3) supply for auxiliaries (4) centralized control.

Each of these features, will, of course, be recognized as embodying well established principles. However, an outstanding characteristic of the Ohio Falls Station is the fact that it utilizes all of these simultaneously and to the utmost. The foresight and courage of the designers of this station thus enabled them to not only construct it at a cost well within the limits for conventional designs, but also permitted them to incorporate in it features which are now becoming recognized as essential for successful and economical operation.

Simplicity is characteristic of the design of this station. The elimination of almost all of the conduit and its wiring has been previously emphasized. One of the basic ideas, however, advanced by Mr. Stanley was to have an electrical control unit near the machine corresponding to the hydraulic control unit. This feature has been accomplished by grouping all of the electrical control features and placing them in a cubicle located adjacent to the governor. Consequently, each unit has its electrical control concentrated at one point and its hydraulic control concentrated at a closely adjacent point. As pointed out in Mr. Stanley's discussion this arrangement while very desirable from an installation standpoint did not seem to permit of economical operation. Consequently, a centralized supervisory control was incorporated. This permitted centralized supervision and control of all of the units through wires in telephone type cables. An immediate result of the decision to use centralized supervision of this character was to reduce to a minimum the number of connections between the centralized supervisory point and each of the electrical control cubicles. Instead of a large amount of conduit and wiring between each generating unit and a central switching point there is only one telephone cable between the electrical and governor control of each unit and the centralized supervising point.

Other important features to be emphasized in the unique design are that the main power circuits and the main control circuits have been shortened to a minimum.

An evaluation of these features indicates that while the electrical controlling equipment may have cost more than a conventional design, yet its installed cost is appreciably less than a conventional design due to the tremendous saving in conduit and control wiring. Besides, the elimination of the majority of this conduit and control wiring has appreciably reduced the inspection and maintenance expense. The net result appears to be a gratifying profit on the investment together with the possibility of very economical extension in the future.

R. M. Stanley: Making one of the largest automatic hydroelectric stations in the world automatic or semi-automatic does not entirely solve the operating problem. With the ordinary switchboard, control panels, instruments, etc. in a centralized control room at one end of the powerhouse or alongside the power house the superimposing of automatic control would constitute an added cost of considerable magnitude.

If, however, ways and means can be found to lessen the cost of the control equipment or its arrangement then automatic control may be justified economically.

This has been accomplished in our plant by using unit control panels and equipment near the units and transformer equipments controlled.

Obviously some centralized control location must exist since we cannot station operators in different parts of the plant; neither can we arrange for operators to travel from one point to another rapidly or efficiently. We substitute, therefore, the miniature switchboard and low-voltage multi-conductor lead-covered control cable for the large central control board and the usual 19/22 control cable and iron conduit.

Part of what we saved in the above manner we expended on automatic equipment.

There is, of course, no particular reason why a non-automatic station could not be equipped and controlled by a centralized miniature switchboard.

When we omitted the large centralized control board we saved the cost of a control room, skylight and foundation (costly on this installation because of the depth to bedrock). Altogether, therefore, the installation is not only convenient and safe but is justified on an economic basis.

The designing engineer must be visionary but practical, and one of his chief problems is to anticipate the future growth of the system, or, if some one else sets up the growth as a basis for a particular design problem, he must foresee clearly how to prepare for this growth so that at the proper time his design proves susceptible of proper expansion, and the future requirements are easily and economically taken care of. Quite often a number of years elapse before it becomes apparent that the design was not quite comprehensive enough and that major alterations are required. These changes in plans or layouts are expensive and

are economic losses which the industry has to bear, especially if rebuilding is necessary.

The miniature switchboard and unit control scheme readily meet this situation.

Suppose for example at the hydro plant a large switching center becomes a necessity. Assume it will be one-third 66 kv.; one-third 13.2 kv.; and one-third 132 kv. A designing engineer working under the old order of things would plan for certain panels—either bench or vertical panels, arranged perhaps in a semicircle or a hollow square with an operator's desk in the center. From the panels would be carried many control wires and conduits buried in walls and floors or run in trenches, on shelves or in large iron pipes or whatnot.

Back of the panels would perhaps be other panels forming another semicircle or hollow square on which would be mounted relays, watthour meters, etc.

The designing engineer must, of course, be prepared with his design for flexibility of panel groupings in case the ratio of number of panels is different from that assumed. Should there be more 132-kv. lines than were figured on or more 66-kv. lines, etc. his design must permit of complete flexibility or extra costs will result and costly changes will be required. Furthermore, the operators may not find the arrangement to their liking after a few years; and, should practises and standards change, the whole arrangement may become out of date, or the number and arrangement of control conduits may be wrong.

Further than this a great deal of money may be wasted in preparation for future equipment—control wire and conduits which may never be required or the requirements for which may be different.

Contrast the foregoing with the situation existing in our hydro plant. We have spent practically no money in advance for future requirements yet how easily such requirements can be taken care of.

If new 66-kv. or 132-kv. or 13.2-kv. or even 4-kv. feeders are required, switching equipment can be installed in the yard adjacent to the plant; unit switchboards—singly or in groups—can be placed near the equipment to be controlled. The miniature board can be extended 4 inches at a time perhaps and low-voltage, low-current multi-conductor cable installed between the miniature board and the unit switchboard. The original hydro plant layout need not be disturbed and a minimum of cost has resulted.

The ease and economy with which additions can be made was realized during the past spring and summer at which time we added a 132-kv. incoming transmission line, a 60,000-kv-a. three-winding 132/66/13.2-kv. transformer bank, a 66-kv. high-capacity oil circuit breaker. No changes in the hydro station have been required and very little money was expended in advance.

The transformers were located on a platform at one end of the plant adjacent to the 13.2 bus and oil circuit breaker rooms.

The 66-kv. oil circuit breaker is located about 600 feet from the plant.

The transformers have load ratio control on the 132-kv. side and there is no 132-kv. breaker.

The 66-kv. winding is connected to the system through the 66-kv. breaker.

The 13.2-kv. winding is connected to the station generating buses through two 13.2-kv. high capacity switches.

A unit type switchboard located at the end of the station controls the 13.2-kv. oil circuit breakers, and the load ratio transformer control on the roof of the 13.2-kv. bus and switch-room is a weather proof electrically heated steel cubicle containing additional panels necessary to the load ratio control equipment operation. Between these is a small number of relatively short control conduits and wiring. Between these unit switchboard cubicles and the miniature switchboard is the small low-voltage low-current multiple lead-covered control cable run in one conduit. Similarly at the 66-kv. oil circuit breaker is a unit type control switchboard in a similar weatherproof electrically heated steel cubicle supervised from the miniature switchboard through the low-voltage low-current multi-conductor lead-covered cable.

One of the benefits realized in this station is that these extensions and additions have not required dangerous work around operating equipment. The hydro station has not been cluttered with construction tools, materials and debris. The operation of the station has not been jeopardized by working on control wiring and conduits near operating equipment as is customary under the old order of things.

We find, therefore, that after three years of successful operation of the original layout and the successful installation and operation of the recent additions that the decided departure from conventional layouts has been entirely justified. We find that the miniature switchboard permits centralized control and supervision in a successful manner and that the application to this station solved the problem of automatic operation and centralized supervision of a considerable amount of apparatus in a very satisfactory manner with a minimum of space and cost and that the future can be taken care of in a cheaper and better manner and without requiring capital expenditures in advance of the actual requirements. It is possible that in the future there may be required a steam turbo generating station near the hydro station.

This station may contain two or more units. There may be two or more step-up transformers. These may step up from generator voltage to 66 kv. or 132 kv. or some other voltage. We may or may not distribute at generator voltage. The old nightmare of the designing engineer does not disturb us.

We can provide space outside the steam plant for any or all of such equipment in any combination which may be required as our system grows and as new apparatus and methods are developed. Unit type switchboard control units in steel weatherproof cubicles or other later types which may be developed can be mounted near the equipment to be controlled and an additional miniature switchboard or switchboards can be installed, connected together by the low-voltage low-current multi-conductor lead-covered cable in one or two iron conduits. And this is not all.

Should we decide that the control of the steam plant and the hydro plant should be in one place we can move the miniature switchboard and its cubicle from its present location to the steam plant. We will not abandon a large amount of control wire and conduit; we will merely move a relatively small amount of low-voltage low-current multi-conductor lead-covered cable. Thus our problem of looking into the future becomes a very simple one and we need not attempt to decide far in advance requirements for the future which at best can only be guessed at and speculated on, especially in situations similar to ours. Therefore, if engineers and executives will study this method of centralized control by miniature switchboards there will surely be found many applications where economic advantages may be realized and great relief from troublesome system planning may be had, and better all around results obtained when actual developments are made.

The Application of Hydrogen Cooling to Turbine Generators

BY M. D. ROSS*

Associate, A. I. E. E.

Synopsis.—Hydrogen has many advantages over air when used as a cooling medium for rotating machines such as reduction of windage losses, increase in available output for a given amount of active materials and the absence of corona effects on the insulation in high-voltage machines.

The paper describes a liquid sealing gland developed for use with turbine generators to prevent escape of gas along the shafts. Two 7,500-kv-a., 3,600-rev. per min. generators with hydrogen cooling have been built and tested. The second machine with the control apparatus is described in detail, and the operating performance over a period of 3½ months is given.

With the development of suitable sealing glands and control apparatus to the point where reliable operation can be expected over long periods, the use of hydrogen cooling for turbine generators appears to be desirable at the present time in ratings of 30,000 kw. and up.

INTRODUCTION

THE development of large turbine generators has recently progressed very rapidly, so that the turbine generator of today is considerably smaller, more reliable, and more efficient than the corresponding machine of five years ago. The improvement is largely due to such factors as better methods of ventilation, stronger rotor steels, lower loss armature laminations, and improved methods of insulating rotor windings. The present indications are that future improvement along the lines of present construction will be relatively slow. In recent designs for the largest machines at any given speed, there are indications that we are approaching the limits of possible ratings using the present materials and methods of construction, and accepted performance characteristics. Any marked change in performance or maximum size will probably be the result of a radical change in design.

A great deal of research has, therefore, recently been carried out in connection with the ventilation of rotating machinery by means of gases other than air. A survey of the available gases shows that hydrogen is the most suitable gas for this purpose, due to its low density (about 7 per cent that of air) and high heat transfer characteristics with forced convection. As the windage losses vary approximately in proportion to the gas density, they can be reduced to a negligible figure with hydrogen. This is an important feature in turbine generators where the windage losses are relatively high. Hydrogen can be obtained readily in large quantities and is a relatively low priced gas. Helium, which has somewhat poorer properties as a cooling medium and is non-explosive, is not available in sufficient quantities for this purpose. Its density is about twice that of hydrogen so that windage losses in helium would be somewhat higher.

ADVANTAGES OF HYDROGEN AS A COOLING MEDIUM

The advantages of hydrogen as a cooling medium have been covered by a number of writers.[1] Briefly, they are as follows:

1. Windage losses are reduced to about 10 per cent of their value in air with a gas mixture containing 97 per cent of hydrogen by volume. The efficiency of large turbine generators would be improved 0.6 to 1 per cent at full load, 1.2 to 2 per cent at half load, with hydrogen cooling, depending on the size and type of ventilation of the machine.

2. With hydrogen the temperature rise of the gas in passing through the machine is lower than with air, due to the lower losses to be absorbed. The surface temperature differences are considerably reduced with hydrogen and the thermal drops, through insulation where air pockets are present, are lower than with air. For a given amount of active materials the rating of the generator with hydrogen cooling would be at least 25 per cent greater than the rating available with air cooling.

3. Corona has little, if any, effect on insulation in an atmosphere of hydrogen. Insulation operating in hydrogen should, therefore, have a much longer life than in air. The windings would also remain free from dirt, a condition which is difficult to obtain in air cooled machines, even where recirculation of the cooling air is used, as there is always some leakage of air at the shafts and around the duct work.

4. Fires in the generator cannot occur, due to the absence of oxygen. No special fire protection apparatus would, therefore, be required with a hydrogen cooled generator.

5. Due to the better heat transfer and the lower total losses with hydrogen, the gas coolers would be smaller and would require less cooling water as compared with an air cooled machine.

APPLICATION OF HYDROGEN COOLING TO SYNCHRONOUS CONDENSERS AND TURBINE GENERATORS

A number of hydrogen cooled synchronous condensers is now in service and this type of machine is growing in popularity, as indicated by the number now on order. As the synchronous condenser does not

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have to be mechanically coupled with any other apparatus, it can be readily enclosed in a gas tight casing with provision for cooling the hydrogen gas and recirculating it. The problem so far as hydrogen cooled turbine generators are concerned is somewhat different as the generator shaft must be brought out through the gas tight enclosure, in order to couple it to the turbine. It is also desirable to bring the collector end shaft outside the enclosure, in order to permit work on the field collector ring brushes while the machine is in operation. This is an important feature in turbine generators which are sometimes run six months or more at a time without a shut-down.

Shaft Seals for Turbine Generators

One of the most important developments in connection with hydrogen cooling for turbine generators has been the design of sealing glands to prevent gas leakage around the shafts where they come out of the gas tight enclosure. Experimental work was started in 1925 to develop a seal. A survey of various methods

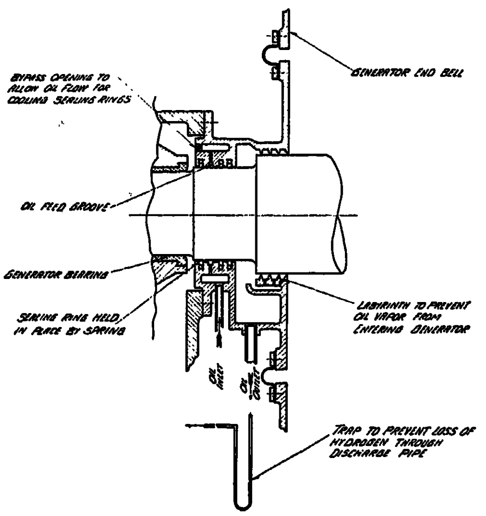

Fig. 1—Cross-Section of Sealing Gland for Turbine Generators

was made and a liquid seal employing oil as the sealing medium was adopted. The seal must be fitted to a shaft somewhat larger in diameter than the generator bearing and an oil seal was best adapted to the relatively high shaft speeds involved. Moreover, a suitable supply of oil under pressure could be obtained from the turbine lubrication system. The sealing gland is shown in Fig. 1. The main body of the sealing gland consists of a casting surrounding the shaft, split on the horizontal center line. A part of the inner bore of the casting is machined to have a clearance around the shaft slightly greater than the clearance in the generator bearing. Oil under pressure is fed into a groove in the center of the seal and flows both ways over the shaft. The flow of oil is throttled to a minimum by fitting three small brass rings in grooves in the seal casting, which are held lightly on the shaft by coil springs. These rings are free to move radially with the shaft. The oil film between the shaft and the seal casting is sufficient to stop the flow of gas at this point, provided the oil pressure is higher than the pressure of the gas in the machine. Oil leaving the hydrogen side of the seal is collected in a chamber in the seal casting and is returned to the main oil supply through a trap, which prevents loss of gas through the drain pipe. Due to the rings in the seal, only a small quantity of oil passes over the shaft and the amount of hydrogen carried out in the oil is very small. No special detraining tanks are required to separate the hydrogen from the oil before returning the oil to the main system.

The power loss in the seal is relatively small. To insure low ring temperatures, some oil is by-passed through a passage around the outside of the ring assembly for cooling purposes. This oil and that discharged along the shaft is returned to the system along with the oil from the generator bearings.

An experimental sealing gland was built in 1926 to determine the performance that could be expected in seals for large generators. The seal was designed to be suitable for a 7,500-kv-a., 3,600-rev. per min. generator. Tests showed that the loss of hydrogen in the oil was negligible, but that a certain amount of air in suspension in the oil entered the enclosure. This amounted to about 0.7 cu. ft. per day. Assuming two such seals in operation, about 70 cu. ft. of hydrogen of 99 per cent purity would be required to maintain the percentage of hydrogen in the machine at 97 per cent. The cost of this gas would be about 70 cents per day. It is not likely that the cost of gas for normal operation would be more than two dollars per day with the largest turbine generators. This figure does not include the cost of carbon dioxide and hydrogen for filling the generator after a shut down.

Turbine Generator Built and Tested in 1928

A 7,500-kv-a., 3,600-rev. per min. generator designed for hydrogen cooling and incorporating the sealing gland described above, was built and tested in 1928. While the rating of 7,500 kv-a. was considerably smaller than the sizes of machines in which hydrogen cooling was considered to be commercially feasible, the machine was large enough to allow construction such as would be used in large generators. Tests were made with the generator running as a synchronous motor, and temperature tests were made at zero power factor. With hydrogen cooling, the generator could be rated at 9,375 kv-a., 80 per cent power factor, with approximately the same temperature rises in stator and rotor as when carrying 7,500 kv-a., 80 per cent power factor, with air cooling. The frame structure was built along standard lines with certain modifications to make it gas tight. Tests on this machine indicated that frame structures for hydrogen cooling would have to be considerably different from the air cooled designs, in order to obtain the minimum gas leakage.

DESCRIPTION OF SECOND TURBINE GENERATOR BUILT

A second 7,500-kv-a., 3,600-rev. per min. generator was built and put on test early in 1930, and is in operation at the present time. This machine is shown in Fig. 2 and in section in Fig. 3. In line with standard practise on 3,600-rev. per min. generators, the generator rotor was designed to be coupled to the turbine through a flange coupling, thus eliminating one generator bearing. The generator frame was fabricated from steel plate, with a minimum length of bolted joints. The generator was mounted on a structural steel bedplate at East Pittsburgh for tests. When coupled to the turbine in normal service it would be mounted directly on the foundation side rails. The active parts of the generator are the same as the standard air cooled machine parts, and no particular effort was made to design the machine to obtain the maximum results with hydrogen cooling.

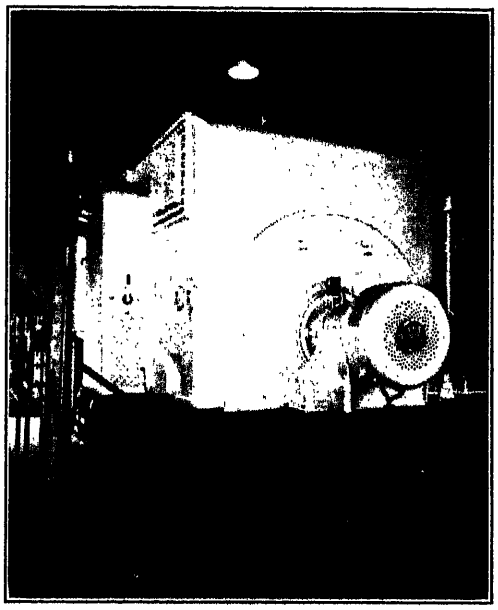

FIG. 2—7,500-KV-A., 3,600-REV. PER MIN. TURBINE GENERATOR ON TEST BEDPLATE

The generator was operated as a synchronous motor during tests

The finned tube gas coolers of Griscom-Russell Co. make are built into the generator frame above the armature core. Straight tube coolers were adopted in order to simplify the construction and to make the cooler sections more accessible for cleaning. Location of the coolers above the generator was considered to involve no operating hazards, as experience with coolers for a large number of machines has never indicated any troubles due to leakage or fractured tubes. One end of the cooler is bolted solidly to the frame and the other end is allowed to move relative to the frame, in order to take up expansion of the cooler tubes. The joint at the free end is made gas tight with a heavy rubber diaphram. The coolers are in two sections, one at each end of the frame, each section being divided into two parts, each of which can be taken out of service and cleaned without disturbing the other parts.

Double enclosing end-bells, split horizontally at the shaft, are provided to carry the gas from the coolers to the fans mounted on the rotor. The frame is designed for the multiple path radial system of ventilation with a single intake chamber at the middle.

The turbine end gland seal is shown in Fig. 4. Two baffle plates are provided in this seal to prevent churning of the oil by the heads of the coupling bolts. These plates are not required in the collector end seal. The seals are bolted rigidly to the ends of the bearing housings, and the sealing rings are located very close to the bearing, so that proper alinement can be readily main-

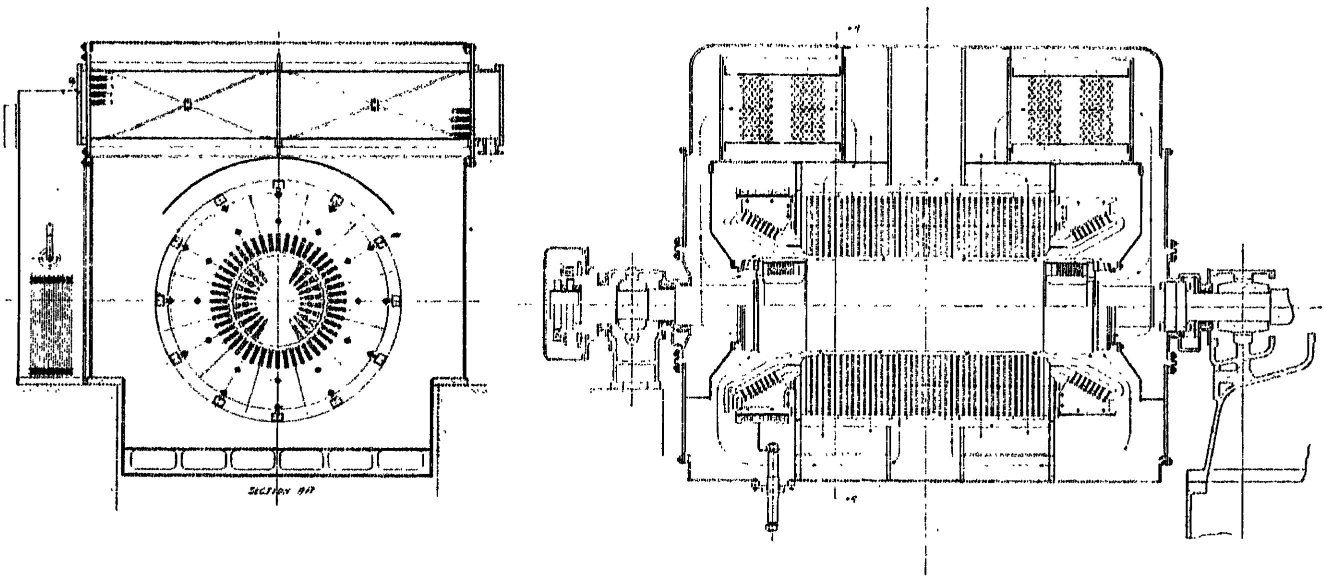

FIG. 3—CROSS-SECTION OF 7,500-KV-A. GENERATOR SHOWN IN FIG. 2

tained. Flexible copper diaphrams are provided between the gland castings and the end-bells, in order to take care of any movement between the pedestal type bearing and the end-bells.

The armature leads are brought out through six gas tight condenser bushings located in a flange on the bottom of the generator. The field leads are carried through holes drilled in the shaft to a point outside the bearing where they are connected to the collector rings. Insulating stuffing nuts are provided to keep the gas from leaking around the field leads.

Description of Gas Control System

A special system for controlling the gas in the machine was developed. The aim in designing this control was to make it as simple and sturdy as possible, so that its operation would be readily understood by the average station attendant. Provision was made for repairing any part of the control mechanism without shutting down the generator.

In filling the generator with hydrogen or in removing

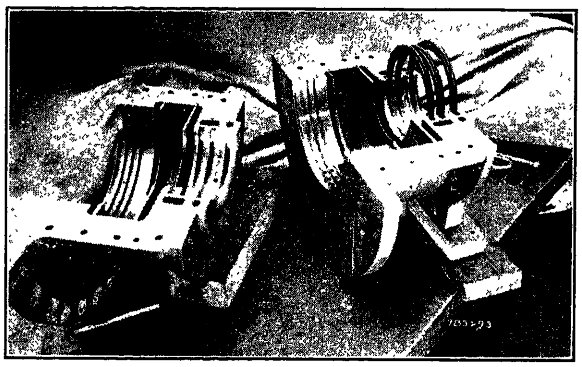

Fig. 4—Turbine End Sealing Gland. The Upper Half is Shown at the Left

the hydrogen, it is necessary to introduce an inert gas in order to avoid an explosive mixture of air and hydrogen. Mixtures between limits of 70 per cent hydrogen and 30 per cent air and 10 per cent hydrogen and 90 per cent air (by volume) are explosive. The highest explosion pressure is developed with about 35 per cent hydrogen and 65 per cent air. Carbon dioxide was selected as the inert gas, due to its density being 50 per cent greater than that of air, so that the percentage of CO_2 gas could be determined by checking the density of the mixture.

Manifolds for hydrogen and CO_2 are provided at some distance from the machine to which standard gas bottles can readily be attached. The hydrogen bottle pressure is reduced to 15 lb. per sq. in. before being fed to the generator. In case of failure of the reducing valve, a safety valve keeps the pressure in the line within safe limits.

The control equipment is mounted in a panel bolted to the side of the generator. This construction was adopted to simplify the piping between the control apparatus and the machine. The layout of the gas piping is shown in Fig. 5, and the electrical circuits in connection with the control in Fig. 6. Both hydrogen and CO_2 supply lines are led to a four-way gas valve on the right hand side of the control, as shown in Fig. 7. With

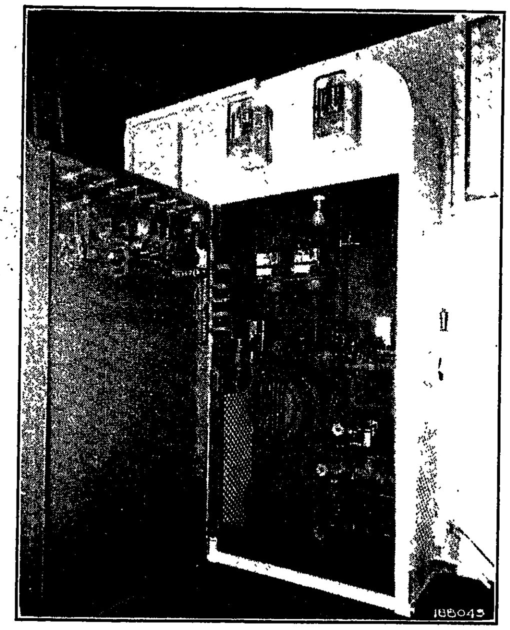

Fig. 5—Gas Control Cabinet

the handle in the "off" position, the control circuits are disconnected from the three-phase, 110-volt supply, and no gas can enter the generator. With the handle in the CO_2 position, CO_2 gas is admitted and a cam

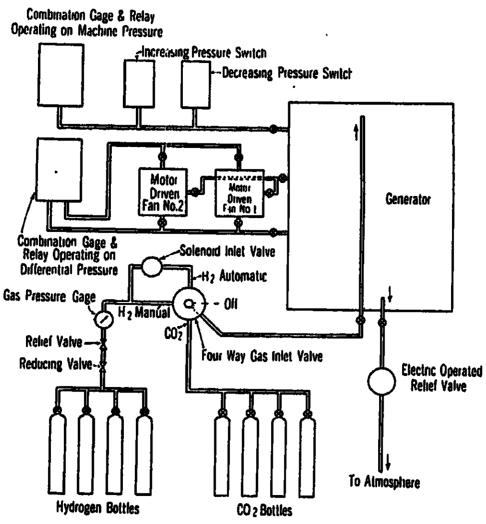

Fig. 6—Diagram of Gas Piping

operated switch on the valve shaft energizes the control circuit.

A small motor-driven fan running at constant speed draws a small quantity of gas from the generator and forces it through an orifice before returning it to the machine. The pressure difference between the two

sides of the orifice is proportional to the density of the gas passing through it. This differential pressure is registered on a gage mounted on the front of the panel. The gage is equipped with contacts controlling a signal which operates when the gas density exceeds a certain value or when the fan pressure drops to zero, indicating that the motor-driven fan has stopped. The motor-driven fans are provided in duplicate, with valves in gas lines, so that one fan can be taken out for repair, without affecting operation of the generator.

When sufficient CO_2 gas has been introduced, as indicated by an increase in the differential pressure gage reading, the control handle is moved to the position marked "Hydrogen Manual," where hydrogen gas can be introduced rapidly through a large valve opening. The differential pressure gage will then show a reduction in pressure as the percentage of hydrogen in the machine increases. When a satisfactory mixture is obtained, the main valve is moved to the automatic position where pressure in the machine is automatically maintained at about 1½ to 2 in. of water by means of an electrically operated needle valve. An electrically operated relief valve allows gas to escape to the atmosphere when the pressure in the machine reaches 2½ in. of water. Both the inlet and relief valves are controlled by pressure operated switches. The relief valve operates when filling with CO_2 and hydrogen as well as when the hydrogen is admitted automatically, but the inlet valve is electrically interlocked so that it cannot open except when the four-way valve is in the automatic position. In removing the hydrogen gas the above procedure is reversed, and the control handle moved from the automatic to the CO_2 position. Carbon dioxide is introduced until the differential pressure gage shows a low enough per centage of hydrogen to allow the machine to be opened up safely.

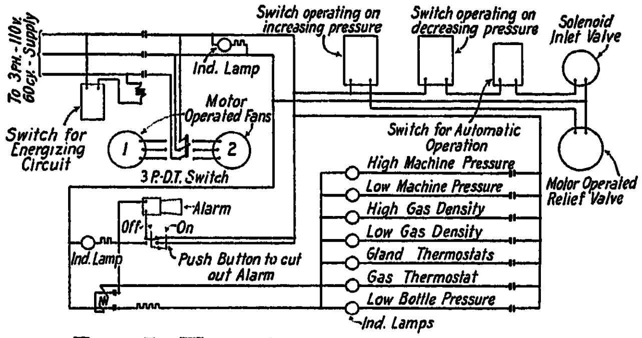

FIG. 7—WIRING DIAGRAM FOR GAS CONTROL

The machine can be filled with hydrogen or scavenged of hydrogen with the generator field rotating or at standstill. With the rotor running so as to insure nearly perfect diffusion, a volume of CO_2 gas equal to about one and one-half times the gas capacity of the machine is required to remove the air. About three volumes of hydrogen are needed to fill the generator with gas of 95 per cent purity. The gas volume of the 7,500-kv-a. generator is approximately 650 cu. ft. About two hour's time is required in filling the machine with hydrogen.

Relays are provided to sound a horn and light a signal light under the following conditions:

1. Machine pressure too high or too low.
2. Gas density too high, indicating contamination of the gas.
3. Gas density meter reading zero, indicating that the motor driven fan has stopped.
4. Low pressure in the hydrogen line feeding the machine.
5. Excessive gland seal temperature.
6. Excessive temperature of the gas in the machine in case of failure of the cooling water supply.

OPERATING EXPERIENCE WITH 7,500-KV-A. GENERATOR

The generator has been operated over a period of 3½ months up to the time of writing this paper. Operation has been satisfactory, and no troubles were encountered with the control and sealing gland features. The glands, when inspected after three months running, showed no evidences of wear, with the tool marks still visible on the sealing rings. The glands required no special attention during this period and the valves admitting oil to them were left open at all times, so that the seals were in operation whenever the oil pump was running. When the generator was shut down with hydrogen in it, the oil pump was kept in operation, in order to maintain the seal at the shafts. Without oil pressure there was some leakage of gas through the sealing glands. In case of failure of the oil pressure, the infiltration of air would probably be very slow.

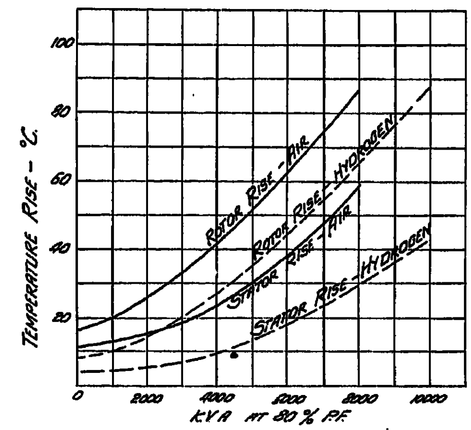

FIG. 8—TEMPERATURE RISES OF 7,500-KV-A. GENERATOR WITH AIR AND HYDROGEN COOLING

PERFORMANCE OF 7,500-KV-A. GENERATOR

The temperature rises of the stator and rotor of the second 7,500-kv-a. generator with air and hydrogen cooling are given in Fig. 8. With hydrogen cooling, the machine could be rated 9,375-kv-a., 80 per cent power factor. The windage loss with hydrogen was 7 kw. as compared with 73 kw. with air, which means an improvement in efficiency of 1.1 per cent at 6,000 kw.,

80 per cent power-factor load. The cooling water required for 9,375 kv-a., 80 per cent power factor with hydrogen cooling was approximately 40 gals. per min., as compared with 80 gals. per min. with air cooling and 7,500 kv-a., 80 per cent power-factor load.

Safety Precautions

The first question usually raised in connection with hydrogen cooling is: what will happen in case of an explosion? With the worst mixture of air and hydrogen, the explosion pressure will be 50 to 75 lb. per sq. in., depending upon the size and shape of the gas chambers in the generator. If the frame is provided with a number of diaphrams which will blow out at rclatively low pressure, the pressures developed will be lower than the above values. The operating hazard for a hydrogen cooled generator with control system such as that described above is probably no greater than that involved in operating other types of control station equipment, and it is, therefore, questionable as to whether frame structures for hydrogen cooled generators should be made explosion proof. No attempt was made to make the two 7,500-kv-a. generators described above to withstand explosion pressures. However, if an explosion-proof frame is considered necessary, it can be built with some increase in cost over that of the lighter frame designed on the basis of gas tightness only.

Desirability of Adopting Hydrogen Cooling

With the development of sealing glands and control apparatus to the point where their operation can be relied upon in continuous service, there is no apparent reason why hydrogen cooling should not be adopted for large turbine generators. The cost of hydrogen gas should not exceed two dollars per day for the largest generators, which would be negligible as compared to the saving in generator losses. The labor cost for operating the generator would be no greater than for an air cooled generator, as the turbine floor attendant can take care of the gas control equipment. While the hydrogen cooled design would be somewhat harder to take apart than an air cooled design, the absence of dirt and corona effects in the machine would probably more than balance that point in estimating the cost of maintenance. With built-in gas coolers, as in the hydrogen cooled machine, considerable space under the generator would be available for removal of condenser tubes and for auxiliary apparatus which is not available with air coolers located below the generator.

The following example will indicate the savings in operating expenses with hydrogen cooling, and the possible capitalization of these savings.

Assuming the following factors:

1. A generator of 100,000 kw. rating at 1,800 rev. per min.
2. Reduction in windage losses with hydrogen cooling—600 kw.
3. Operating time per year—7,000 hr.
4. Value of power at the bus—0.4 cents per kw. hr.

The savings can be evaluated as follows:

Value of power at bus (4,200,000 kw. hr.)	$ 16,800
Less cost of gas at $2.00 per day and cost of hydrogen and carbon dioxide for 3 fillings after shut-down	1,100
Net saving per year with hydrogen cooling	$ 15,700
Capitalization of savings at 15 per cent	$105,000

Preliminary studies of large turbine generators indicate that hydrogen cooling would be desirable in ratings of about 30,000 kw. and up, where the additional cost of the gas-tight-enclosure and the control equipment would be relatively small in comparison with the cost of the generator, and the saving in losses would justify the slight additional complication due to this method of cooling.

Acknowledgment

The writer wishes to acknowledge the early work on hydrogen cooling carried out by Mr. C. J. Fechheimer, Mr. G. W. Penney, and Mr. C. M. Laffoon and others with whom the writer is associated. The sealing gland and method of measuring gas density were developed by Mr. Penney.

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Discussion

S. L. Henderson: With our present knowledge of materials, the maximum possible rating of turbine generators in single machines is approximately 31,250 kv-a. at 3,600 rev. per min. and 200,000 kv-a. at 1,800 rev. per min., with air as the cooling medium. Cooling with hydrogen, therefore, offers the possibility of increasing this upper limit at least 25 per cent. One of the difficulties in the application of hydrogen cooling to turbine generators has been to obtain a proper seal between the shaft and the end-bell, a problem which could be eliminated in the hydrogen cooled s nchronous condenser. The paper shows that the leakage can be controlled within commercial limits, and the density of the gas can be maintained automatically above an explosive mixture.

There is some question whether it is necessary to build these machines explosive proof, and this question is one that can only be answered by experience. The arrangement of coolers within the confines of the machine should be of interest as the machine is complete in itself and does not require the addition of ducts or cooler supports. Such a machine lends itself readily to the outdoor station for being gas proof, it must of necessity be weather proof.

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